CARIBU: A new facility to study neutron-rich isotopes

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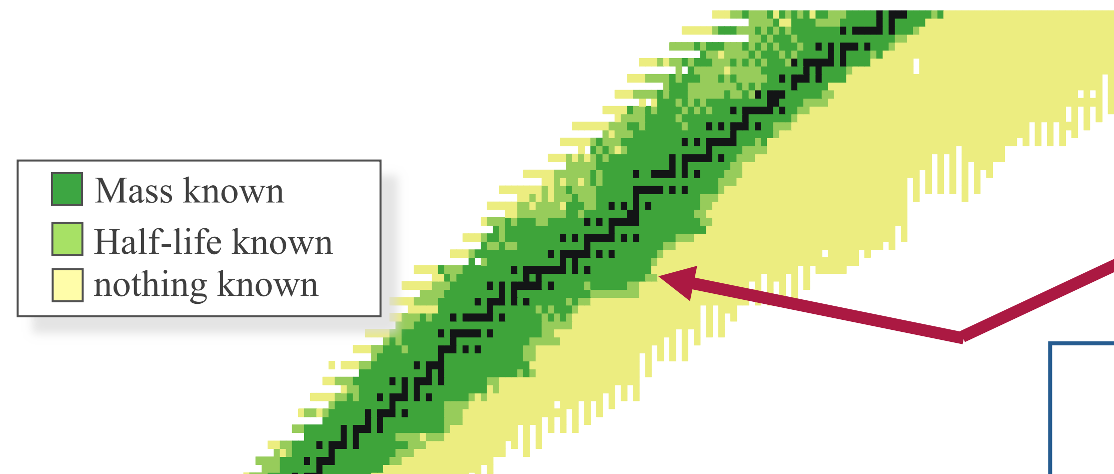
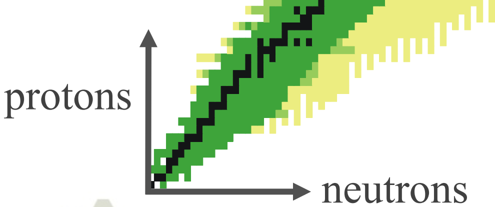
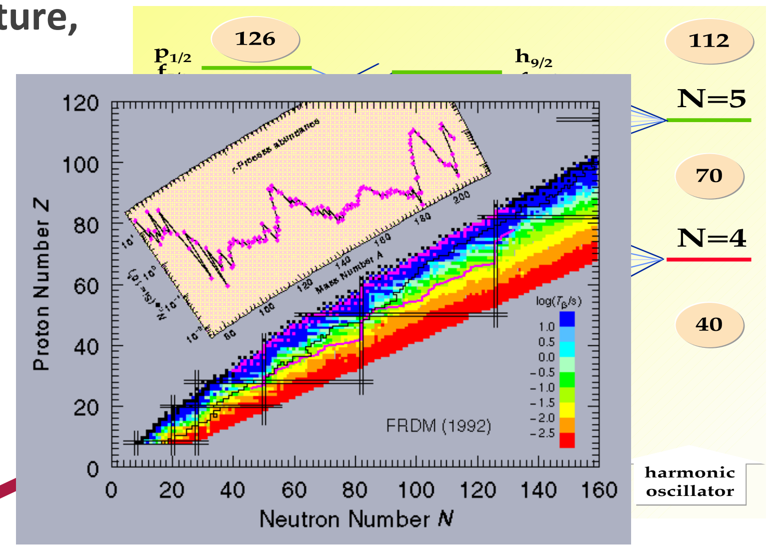
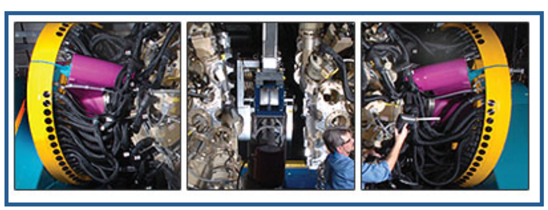
Why CARIBU: nuclear structure of neutron-rich nuclei

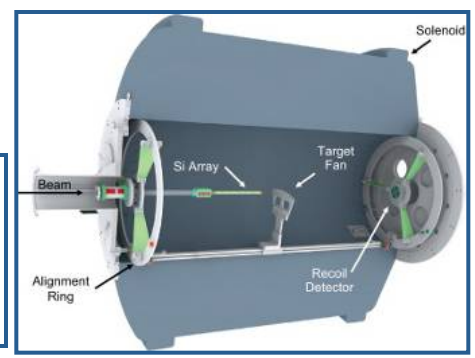
- **Heavy neutron-rich nuclei region:**
  - **region mostly unexplored even for the most basic properties**
  - **weakly bound with diffuse surface … reduced spin-orbit coupling, shell model possibly modified**
  - **signature can take many forms: single particle structure, ground state properties, etc …**
- **r-process path**
  - **Mass, lifetime, beta-delayed neutron**











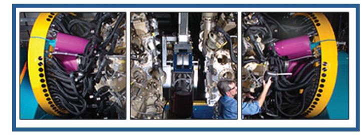
CARIBU - Californium Rare Ion Breeder Upgrade

Access to n-rich region obtained at ATLAS via fission of the most neutron-rich “available” very heavy nuclei (e.g. ^{252}Cf)

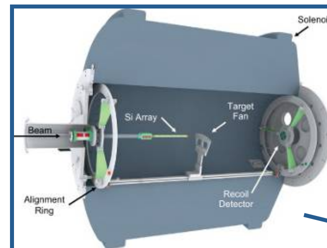
- Project goal: Provide neutron-rich radioactive beams to user community
  - Low-energy
    - Masses, decay spectroscopy, laser spectroscopy, …
  - Reaccelerated through ATLAS at up to 15 MeV/u
    - Single particle structure, gamma-ray spectroscopy, …

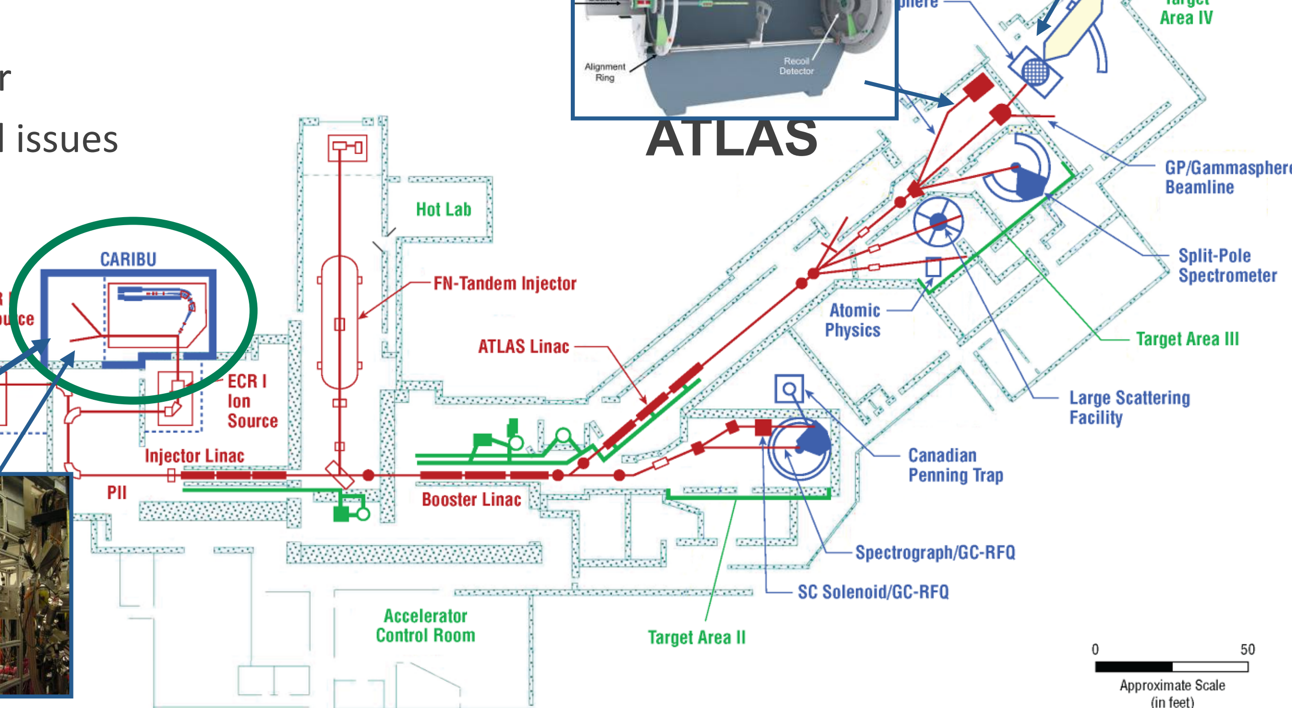
- Project Description
  - Gas catcher/RFQ cooler
  - Source and radiological issues
  - Isobar separator
  - ECR Charge-breeder
  - Diagnostics
  - Experimental equipment

Gammasphere



HELIOS spectrometer





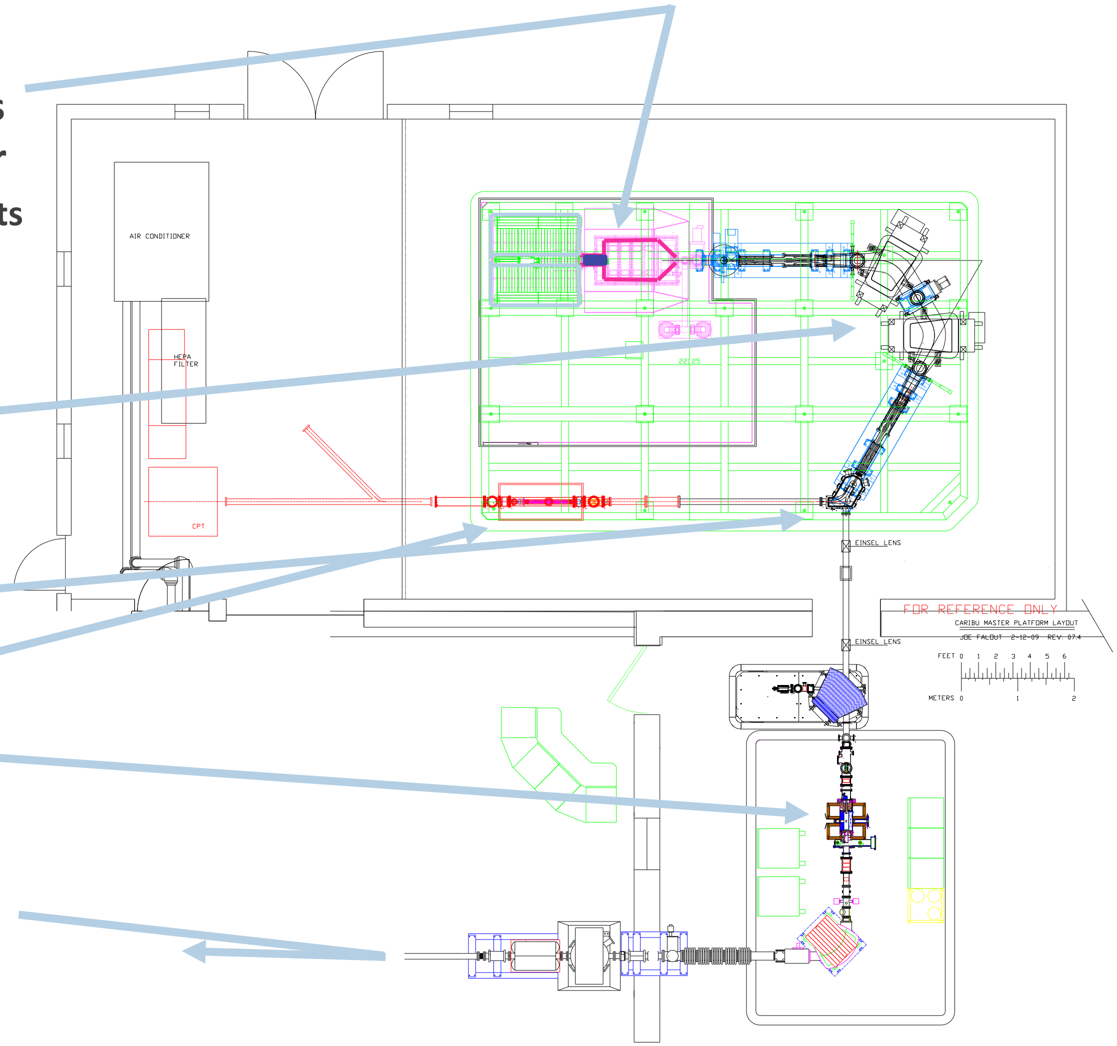
CPT mass spectrometer

X-array

Neutron-rich beam source: CARIBU "front end" layout

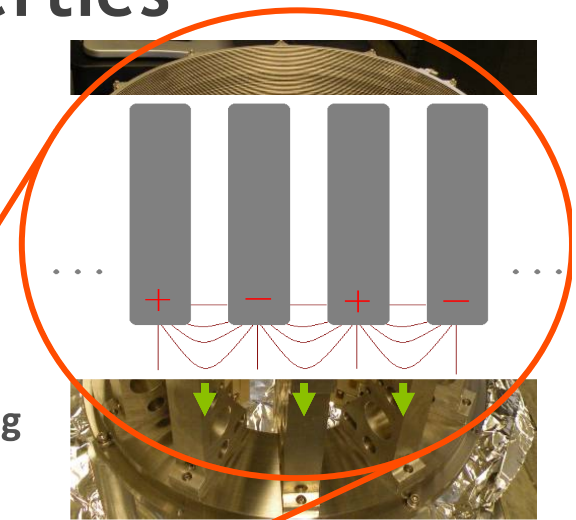
Main components of CARIBU

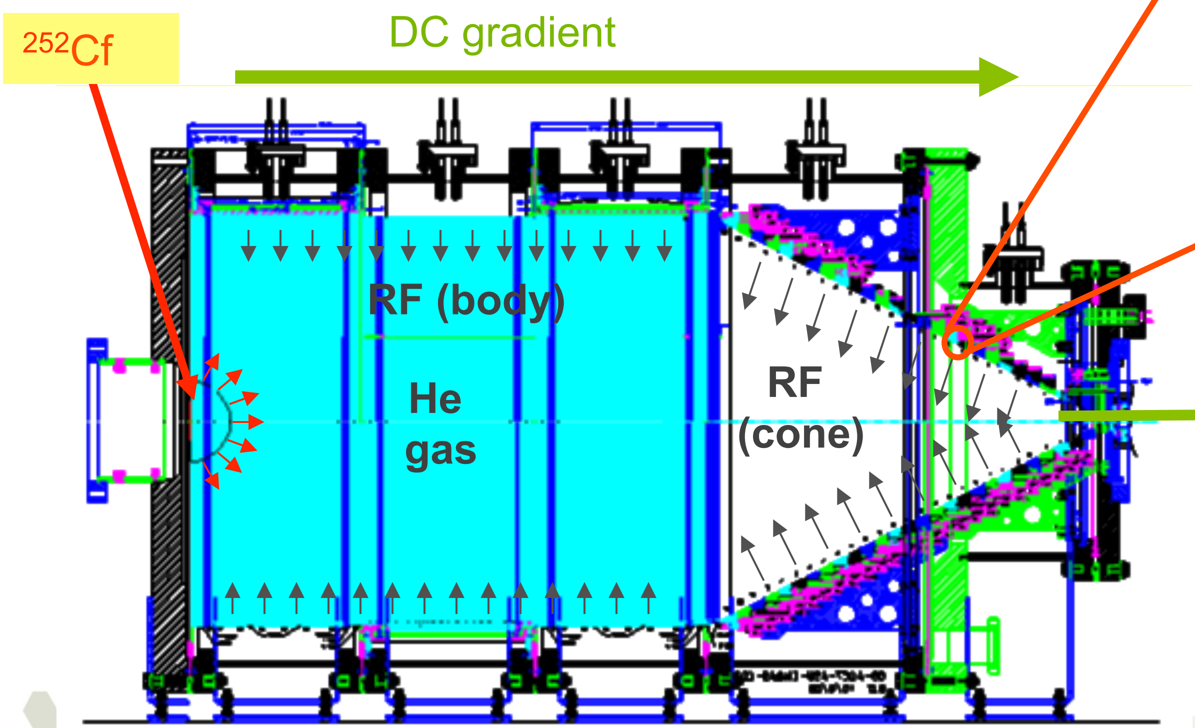
- **PRODUCTION**: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics

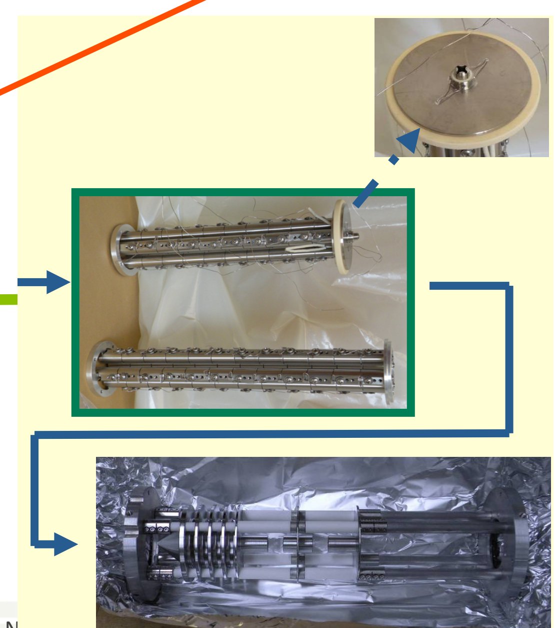


CARIBU gas catcher: transforms fission recoils into a beam with good optical properties

- Based on smaller devices developed at ANL
  - Radioactive recoils stop in sub-ppb level impurity Helium gas
  - Radioactive ion transport by RF field + DC field + gas flow
  - Stainless steel and ceramics construction (1.2 m length, 50 cm inner diameter)
  - Fast and essentially universally applicable
  - Extraction in 2 RFQ sections with μRFQs for differential pumping

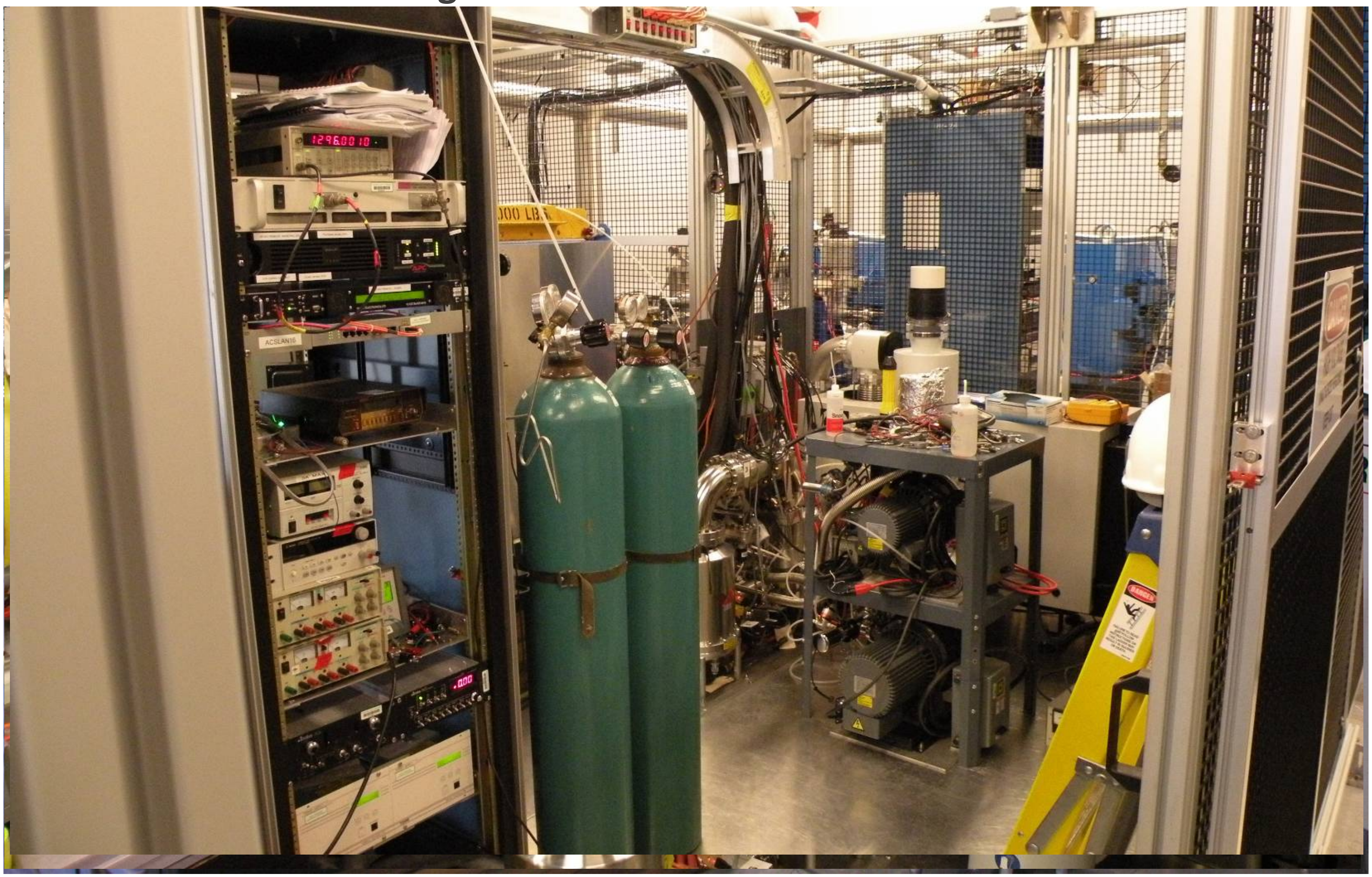






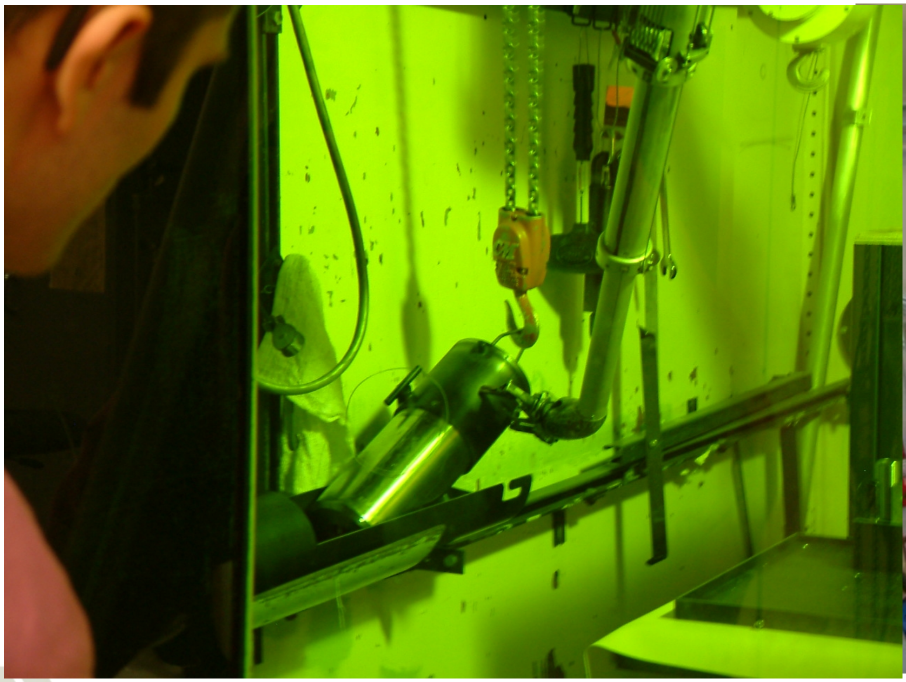
The very large high-intensity gas catcher for CARIBU

- **Gas Catcher/RFQ cooler isolated from main platform and biased to 50 kV.**
- **Installed inside secondary enclosure with pumping, cooling and gas distribution**
- **Under 12000 lbs of shielding**



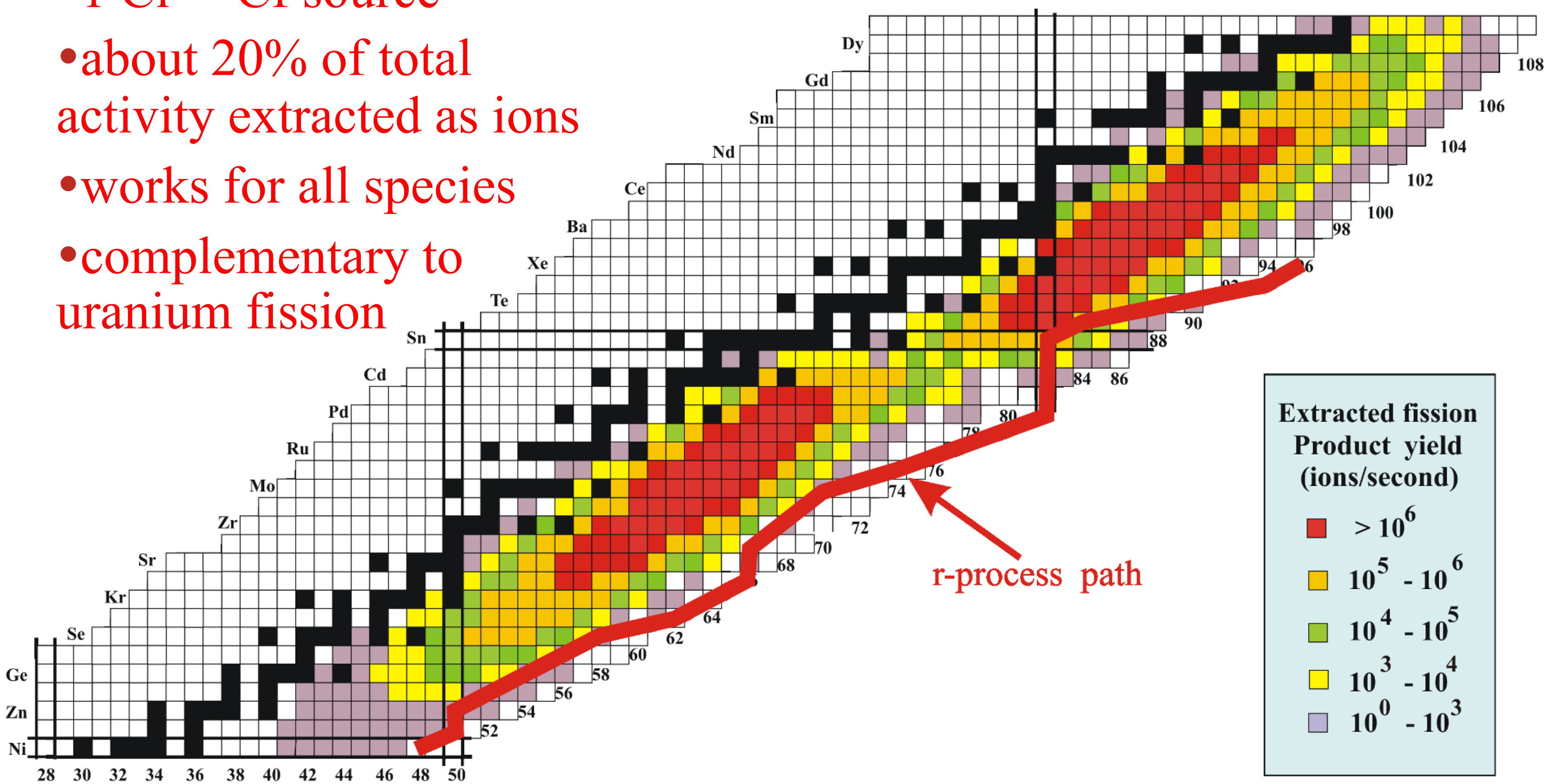
Californium source and transport cask

- Cf source is made at the HIFR high-flux reactor in Oak Ridge (~50 rem/hr unshielded)
  - Progression of 3 sources … 2 mCi, 80 mCi, 1 Ci
- Transported in a steel/cement cask to Argonne
- Installed in the CARIBU transport cask using manipulators in hot cells at Argonne
- Move in the cask on site at Argonne
- For installation in the gas catcher, the source and shielding plug are pushed from the storage location into position at the end of the gas catcher.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.



Extracted isotope yield at low energy (50 keV)

- 1 Ci ^{252}Cf source
- about 20% of total activity extracted as ions
- works for all species
- complementary to uranium fission

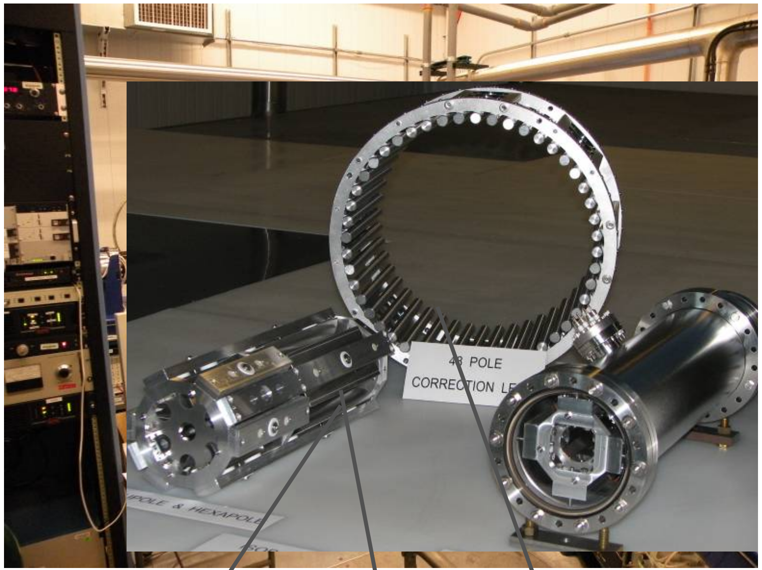


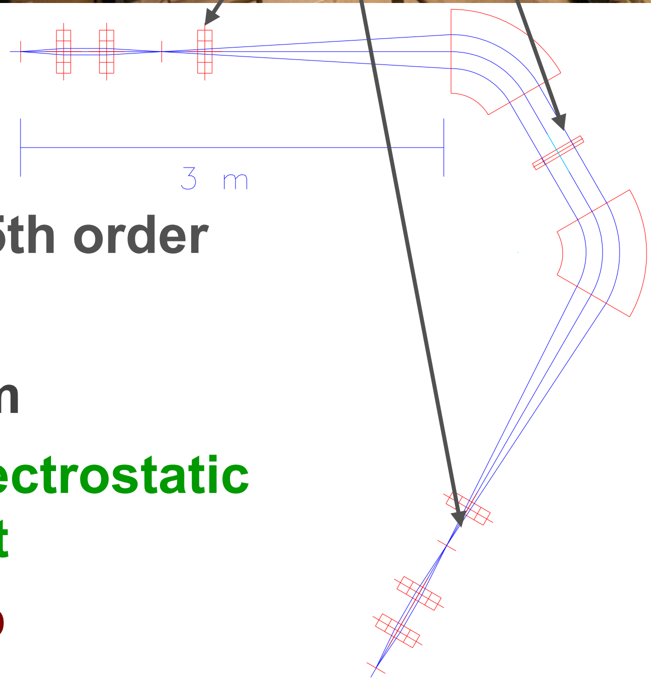
"Compact" isobar separator

- **Need to select specific activity**

•Take advantage of low emittance and energy spread of extracted beams:

Beam Properties from gas catcher:
$\varepsilon \approx 3\ \pi$ mm•mr $\delta E \approx$ 1eV



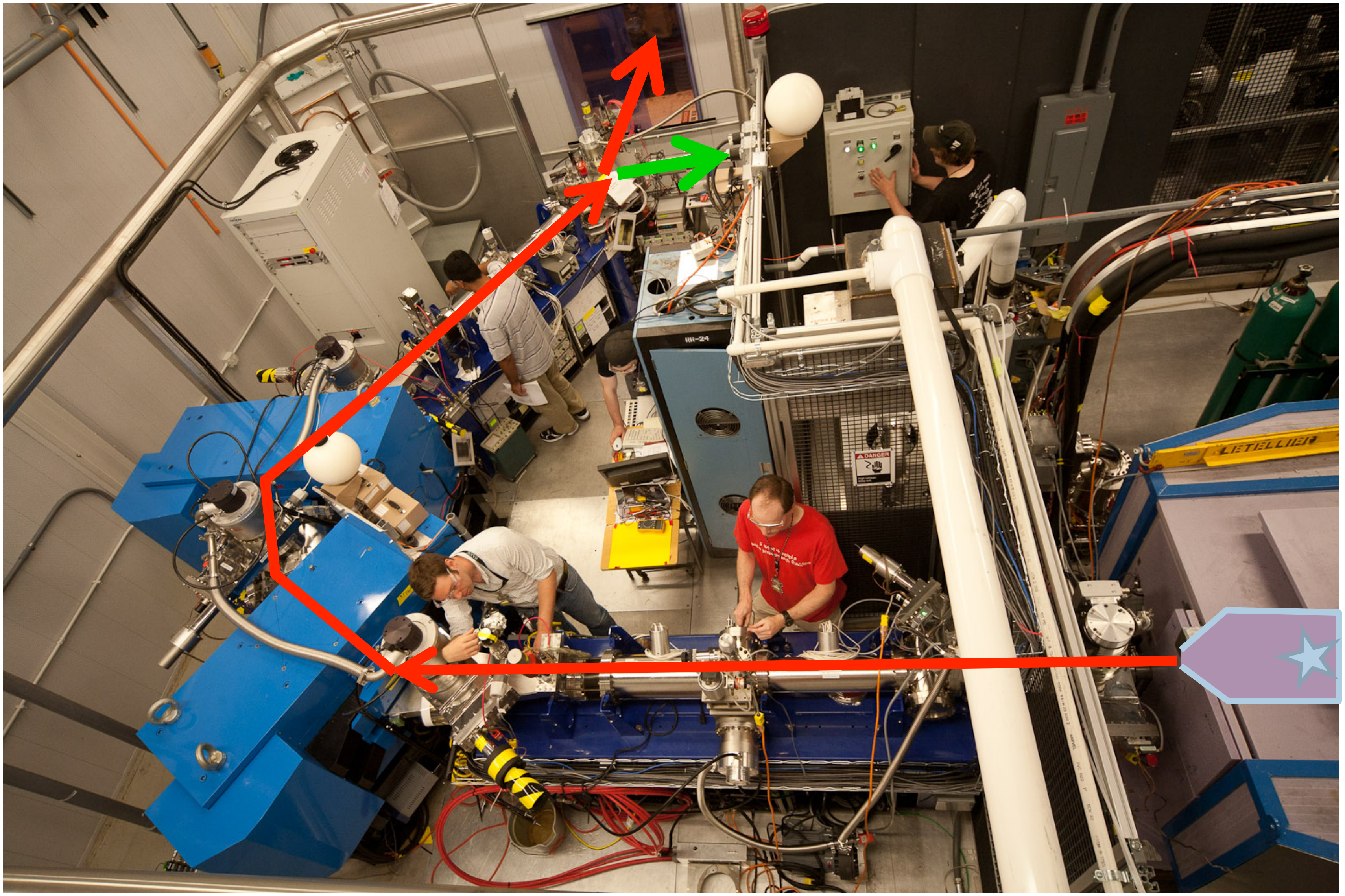


- **Matching sections at entrance and exit transform beam to a ribbon beam.**
- **2 x 60 degree bends, R = 50 cm**
- **3 electrostatic multipoles correct through 5th order**
- **First order mass resolution: 1/20,000**
- **Small enough footprint to fit on HV platform**

•All optics, except for bending magnet, is electrostatic so that tune is essentially mass independent

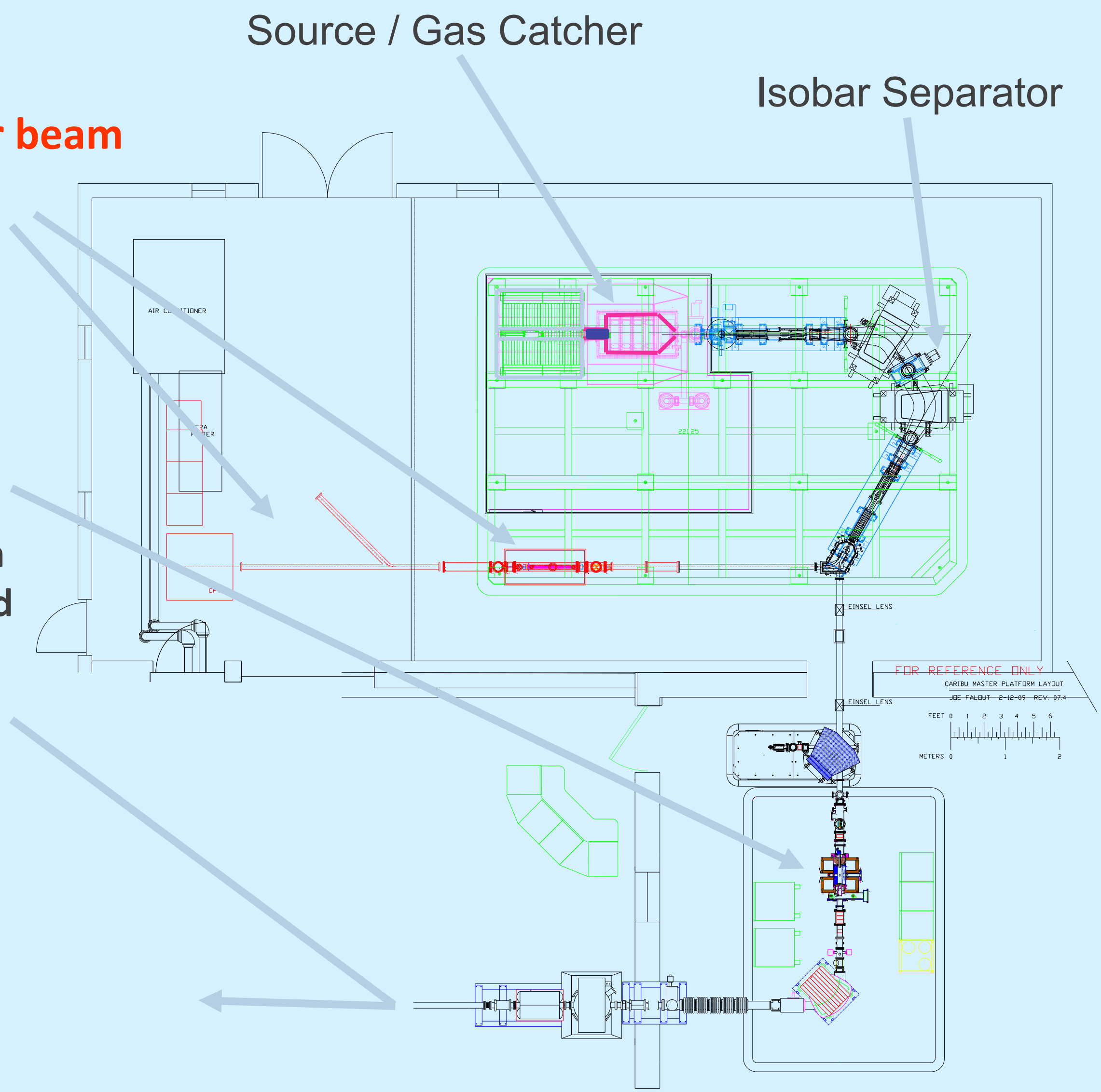
i.e: changing isotope with one knob

Photo of CARIBU w/ beam paths overlay to ECRCB & Trap

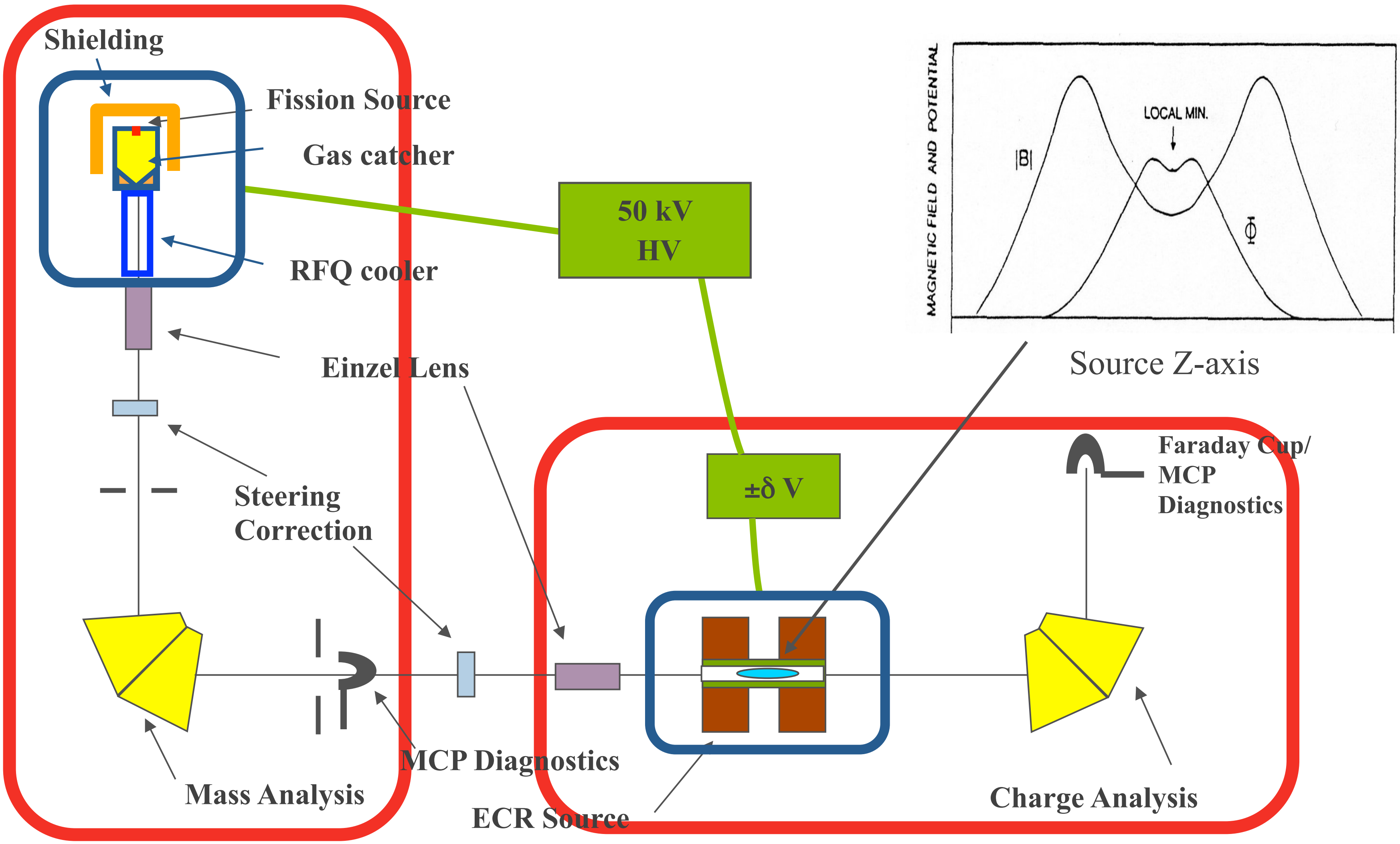


Beam Delivery

- After isobar separation, two options for beam use
- Low energy experiments **after beam bunching**
  - Mass measurement
  - Laser Spectroscopy
  - Beta decay studies
- Reaccelerated Beams
  - Use ECR-1 as charge breeder
  - Inject ions into ATLAS in high charge state (q/m > 0.15) and energy (~100-200 keV)

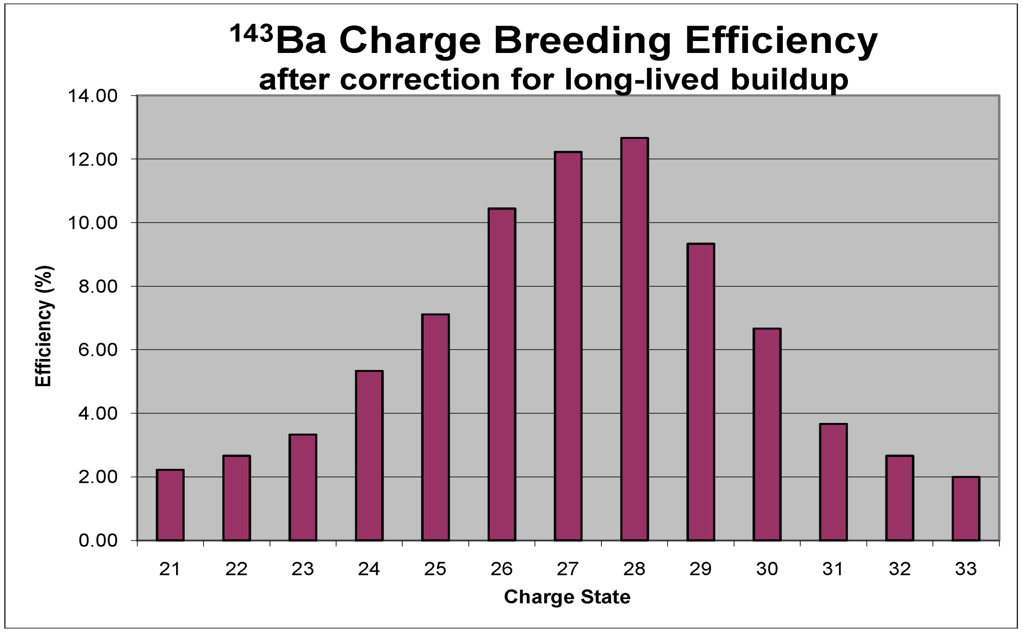


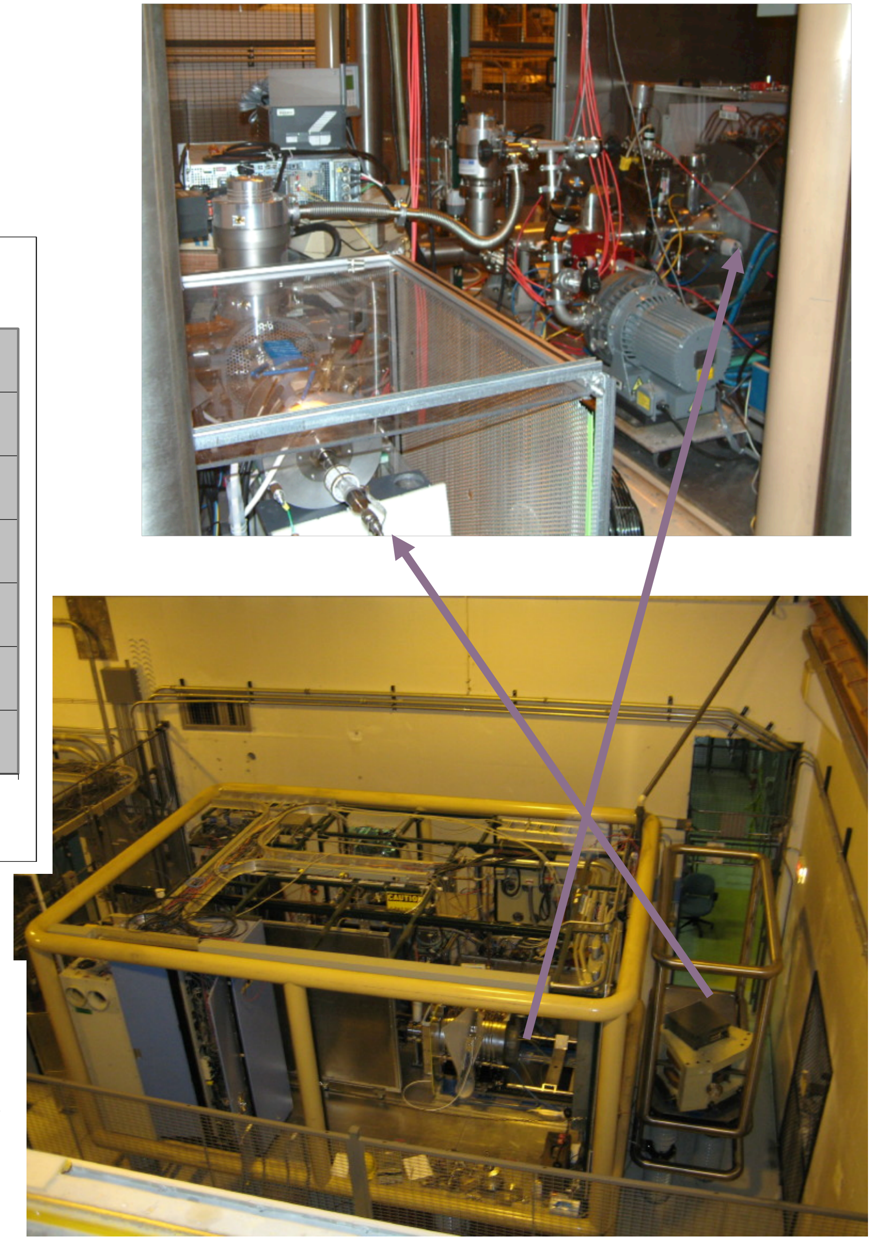
CARIBU ECR Charge-Breeder System



ECR Charge Breeder Results

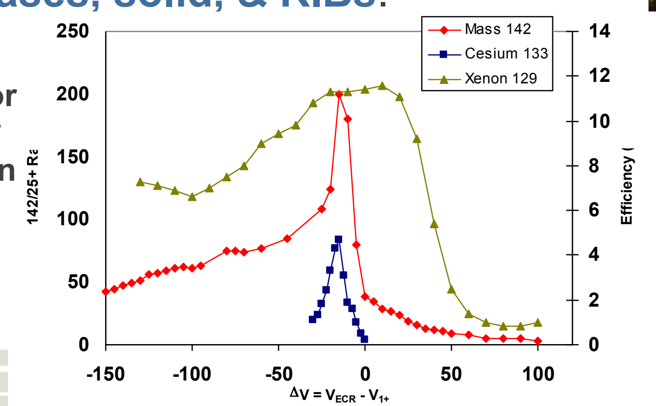
In order to accelerate beams in ATLAS the charge-to-mass ration (q/m) must be raised to >1/8 (depending on the desired energy).



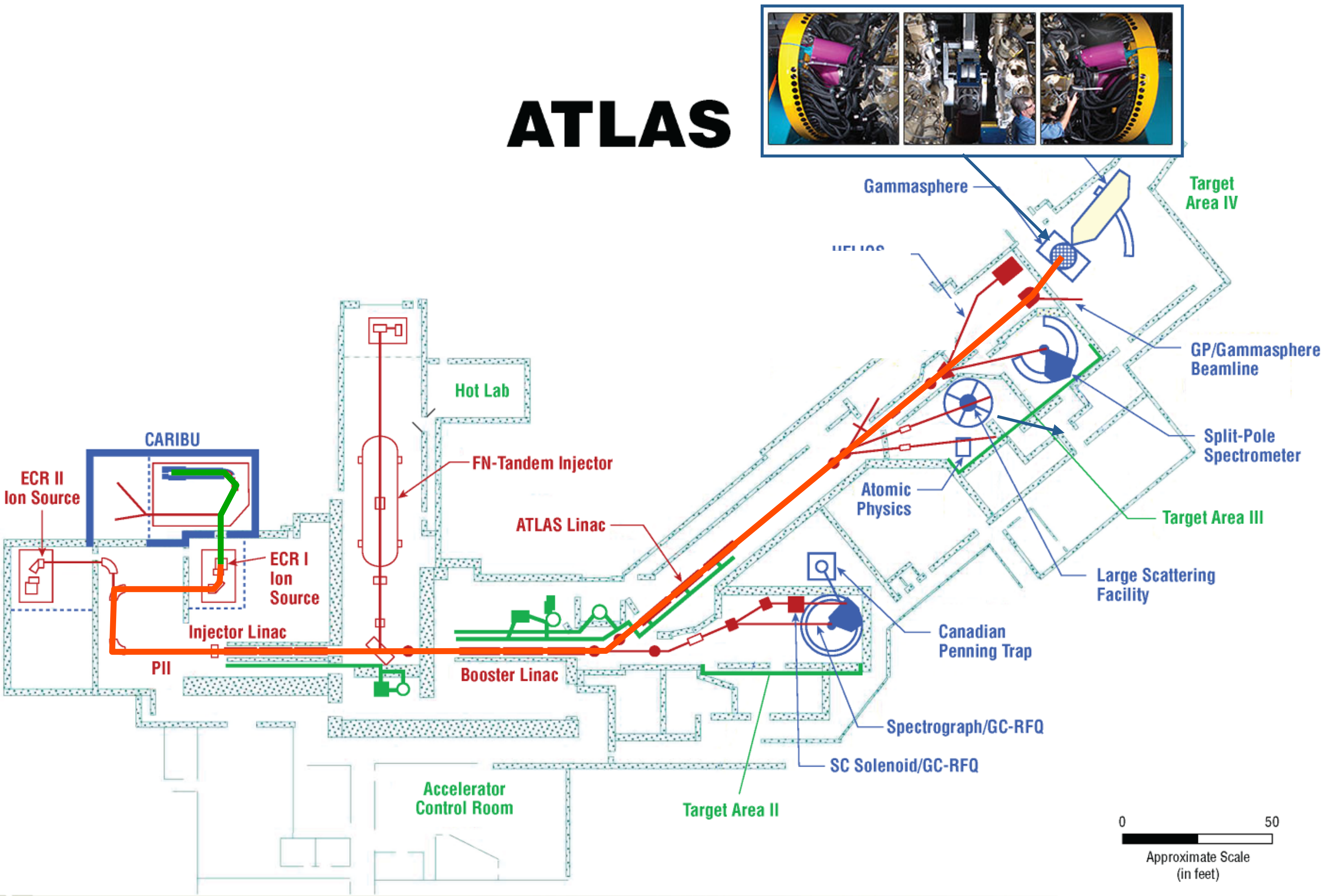


Best breeding efficiencies: 11-16% for all gases, solid, & RIBs.

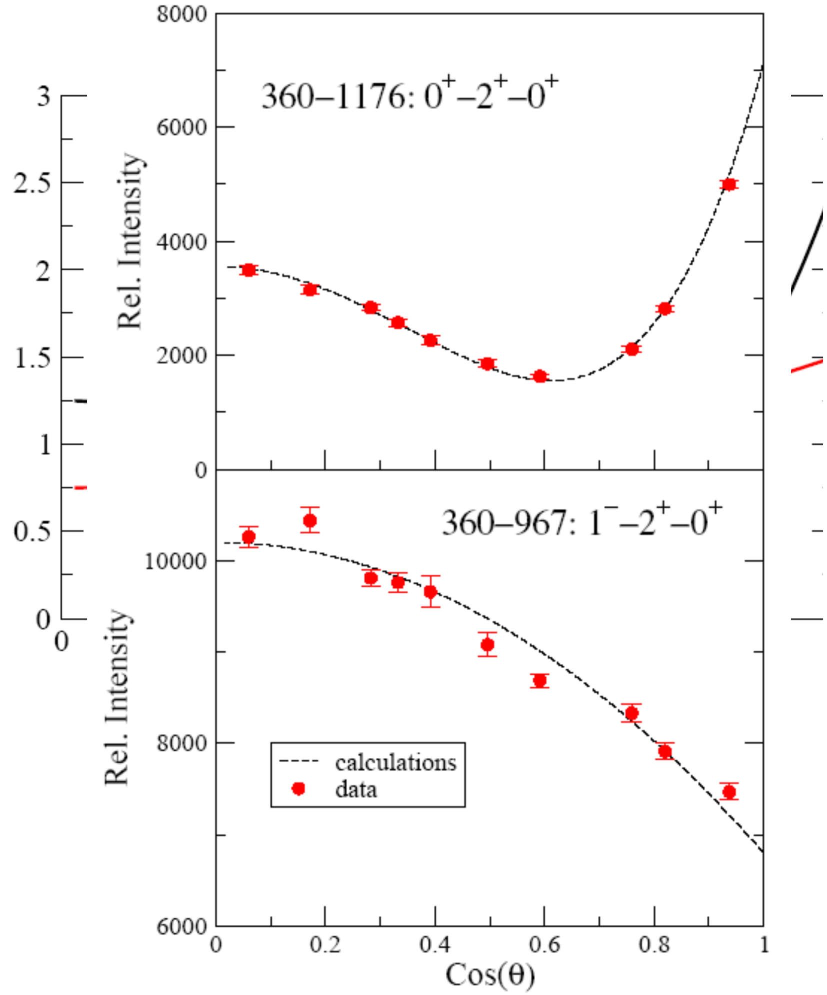
Rate and Efficiency for Mass 142/25+, $^{129}Xe^{25+}$ and $^{133}Cs^{26+}$ as function of Voltage difference between ECRCB & 1+ source

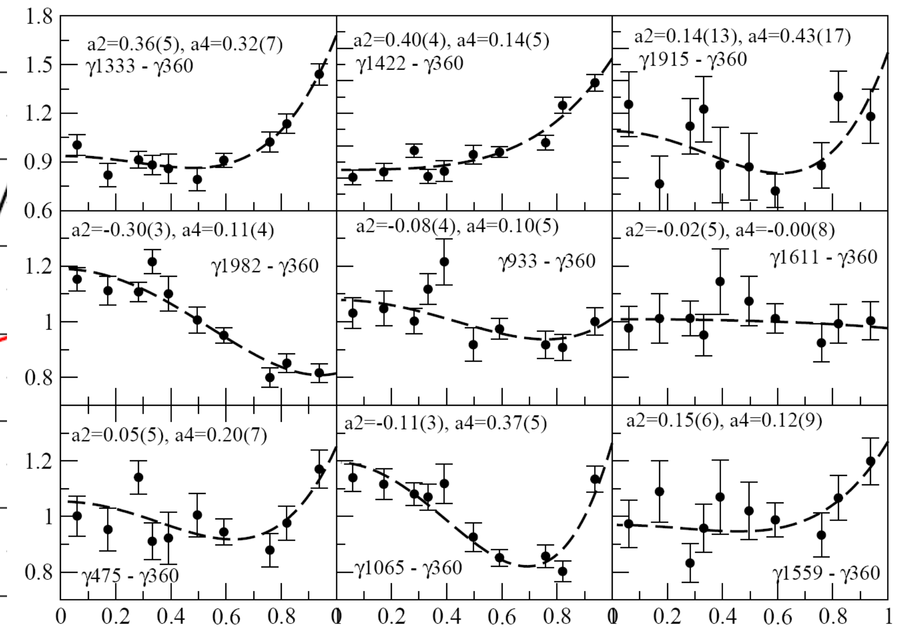


CARIBU beams reaccelerated to Gammasphere



The power of Gammasphere: Spin-Parity Assignments via Angular Correlations



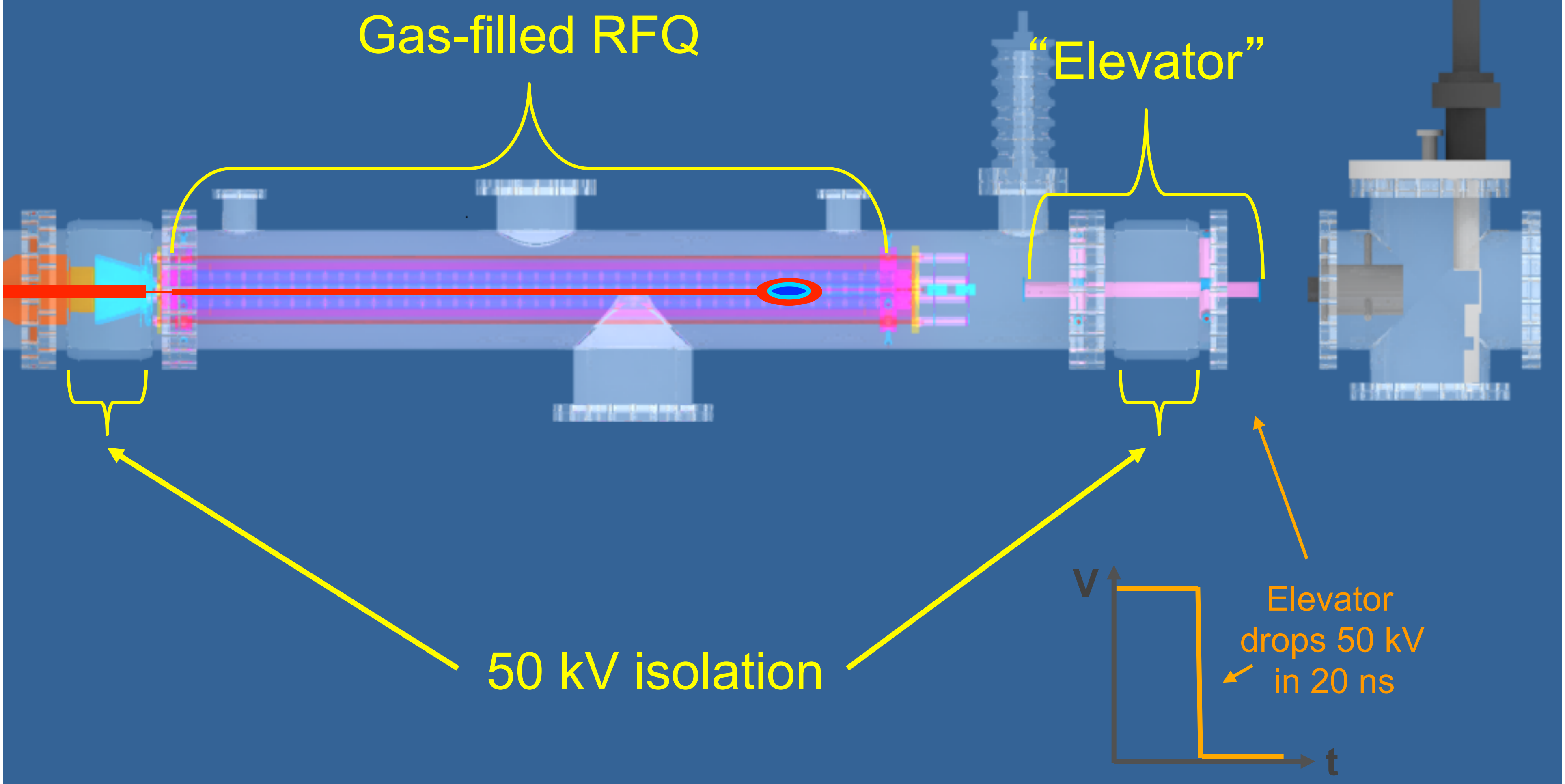


γ−γ correlation in ^{142}Ba
See talk by S. Zhu

Low-energy beamlines: low-energy buncher

- provides a pulse structure on low-energy beam and increases peak intensity by about 5 orders of magnitude

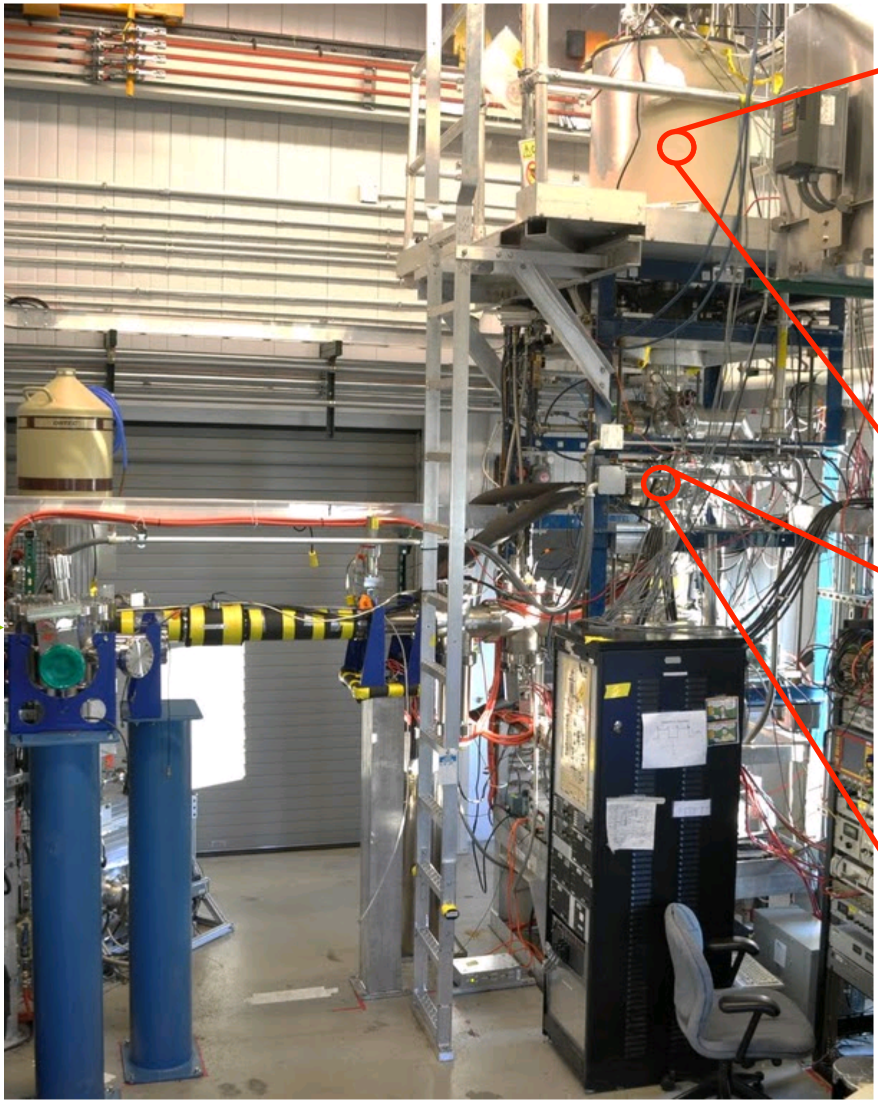
- Allows energy to be tuned from a few 100s of eV to 50 keV



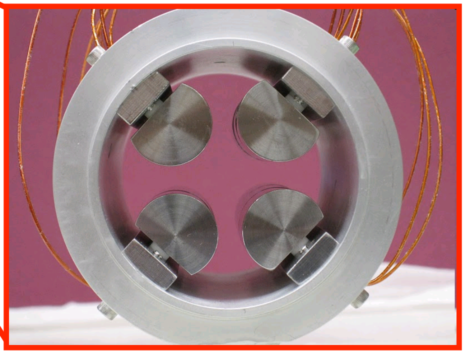
CARIBU, CPT, and tape station

The CPT apparatus at CARIBU

2 kV pulsed beam

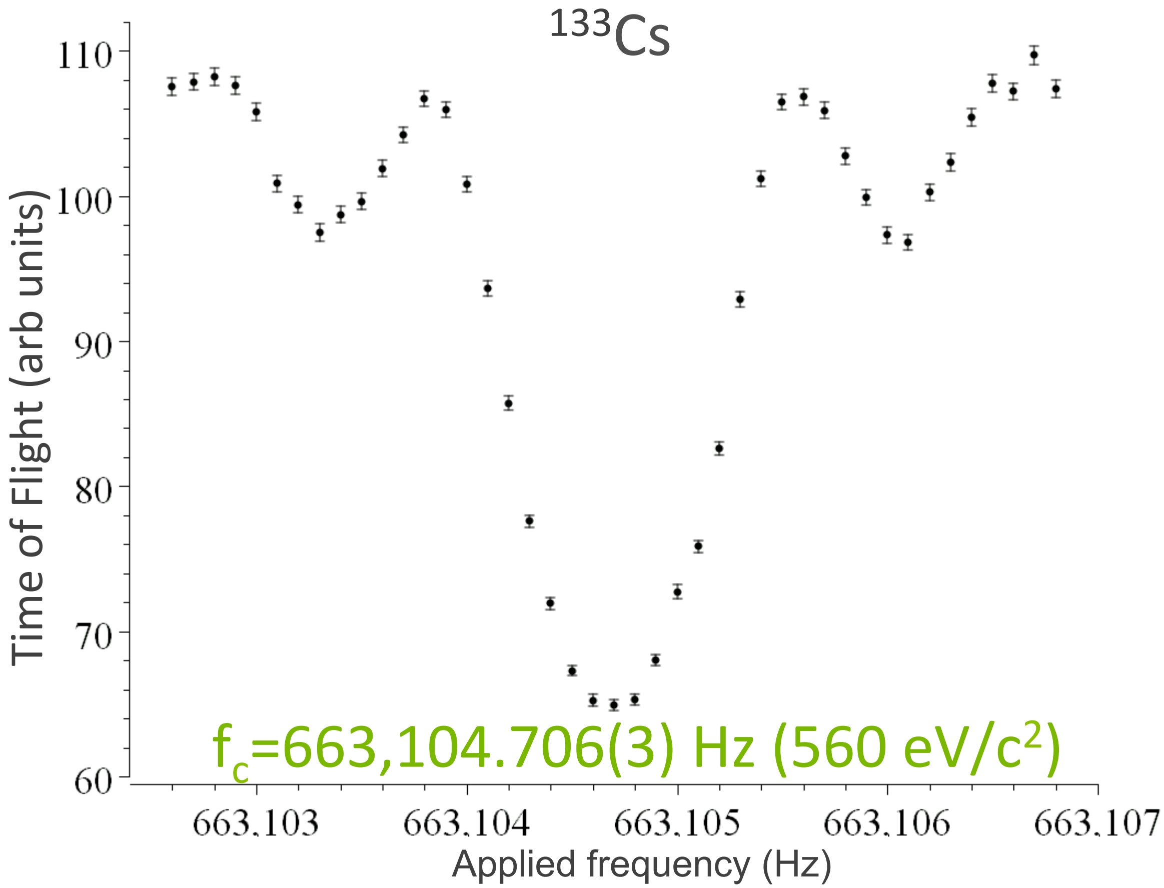


Penning Trap



cryogenic linear ion trap

Time-of-flight technique

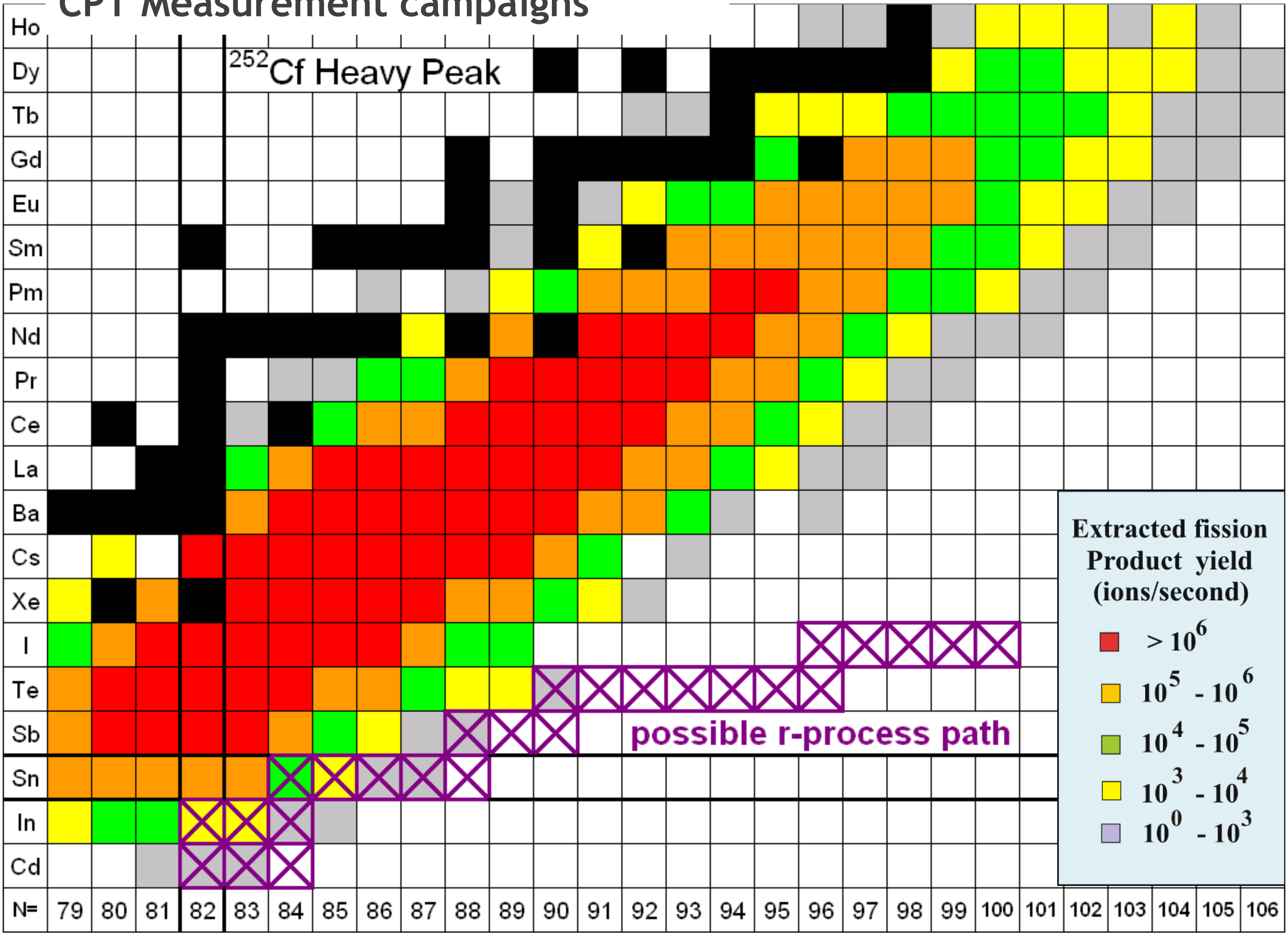


$$\omega_c = \frac{q_c B_c}{m_c}$$

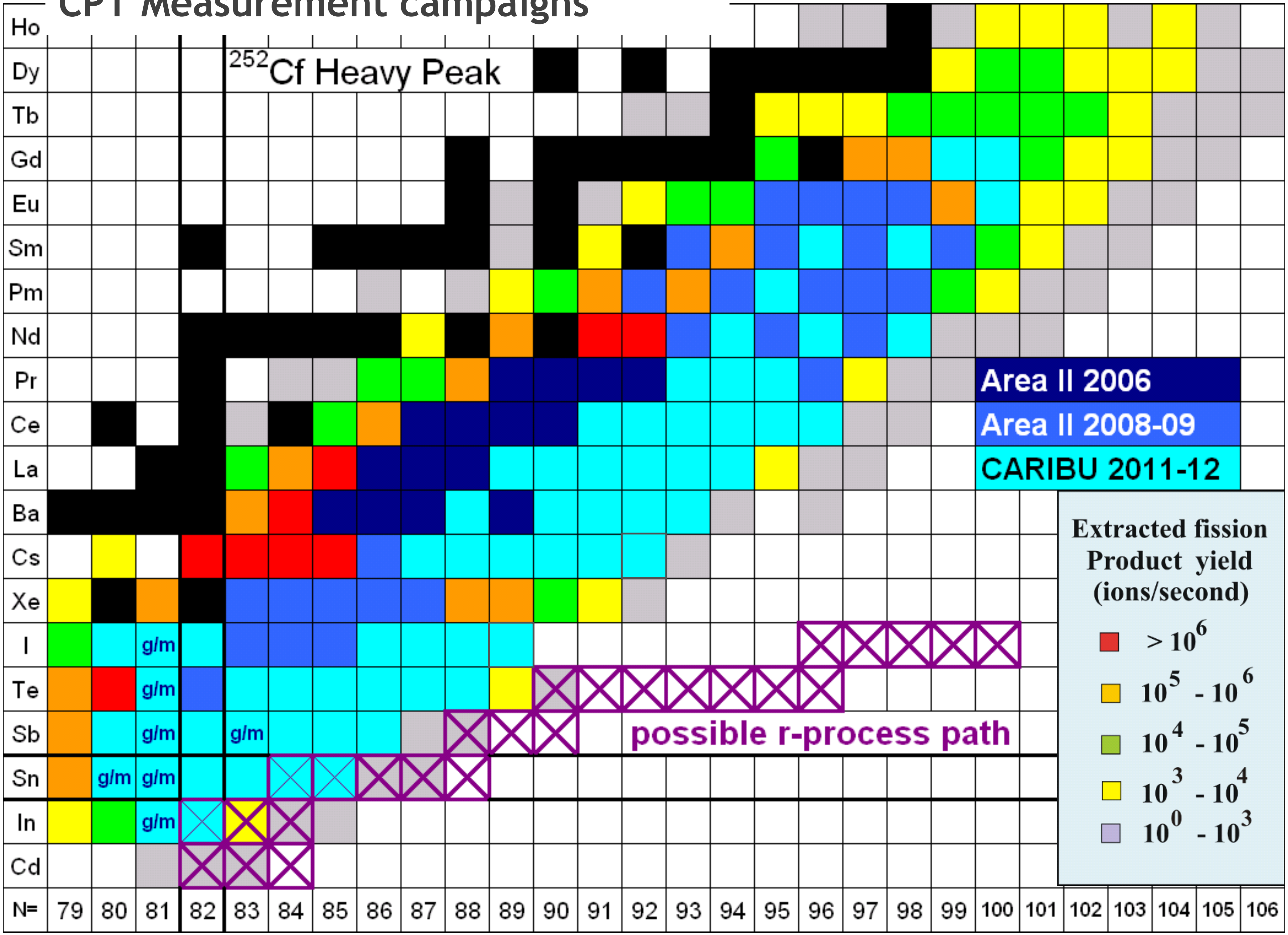
Unknown: $$\omega_? = \frac{q_? B_c}{m_?}$$

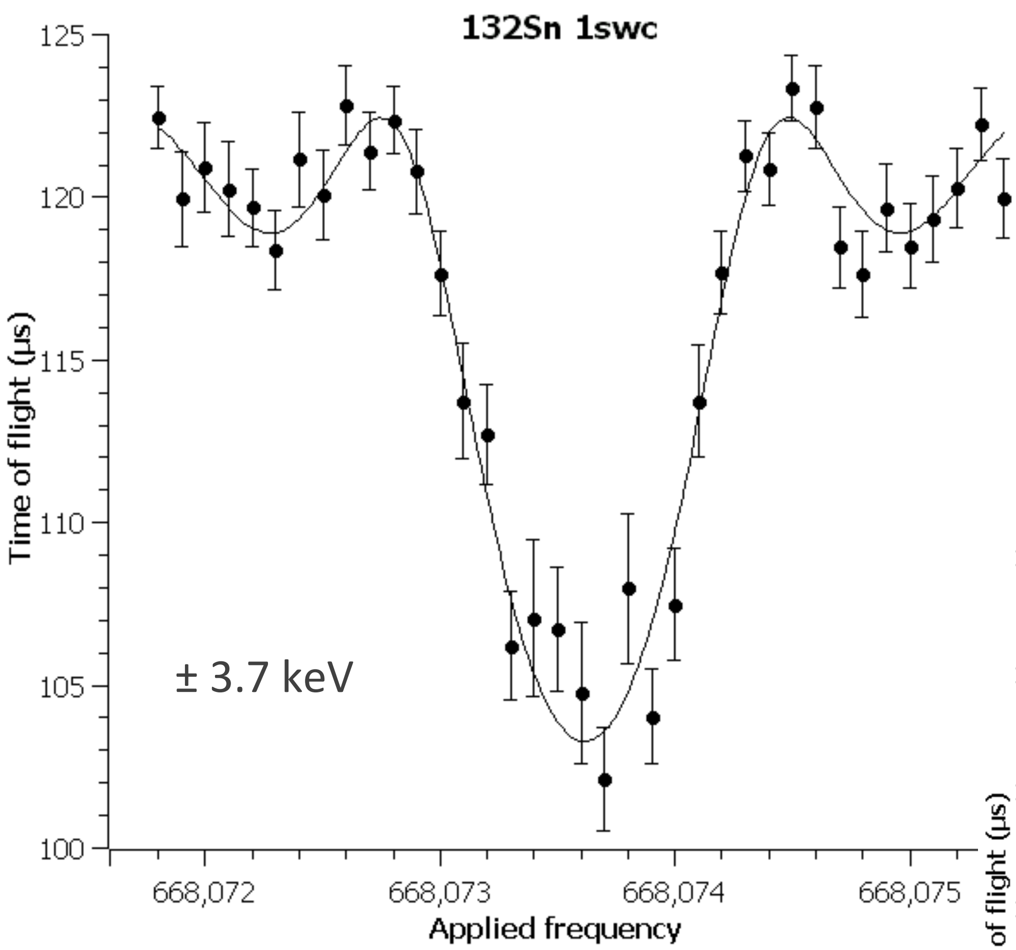
$$\frac{\text{Unknown}}{\text{Calibration}} \Rightarrow m_? = \frac{q_?}{q_c}\frac{\omega_c}{\omega_?} m_c$$

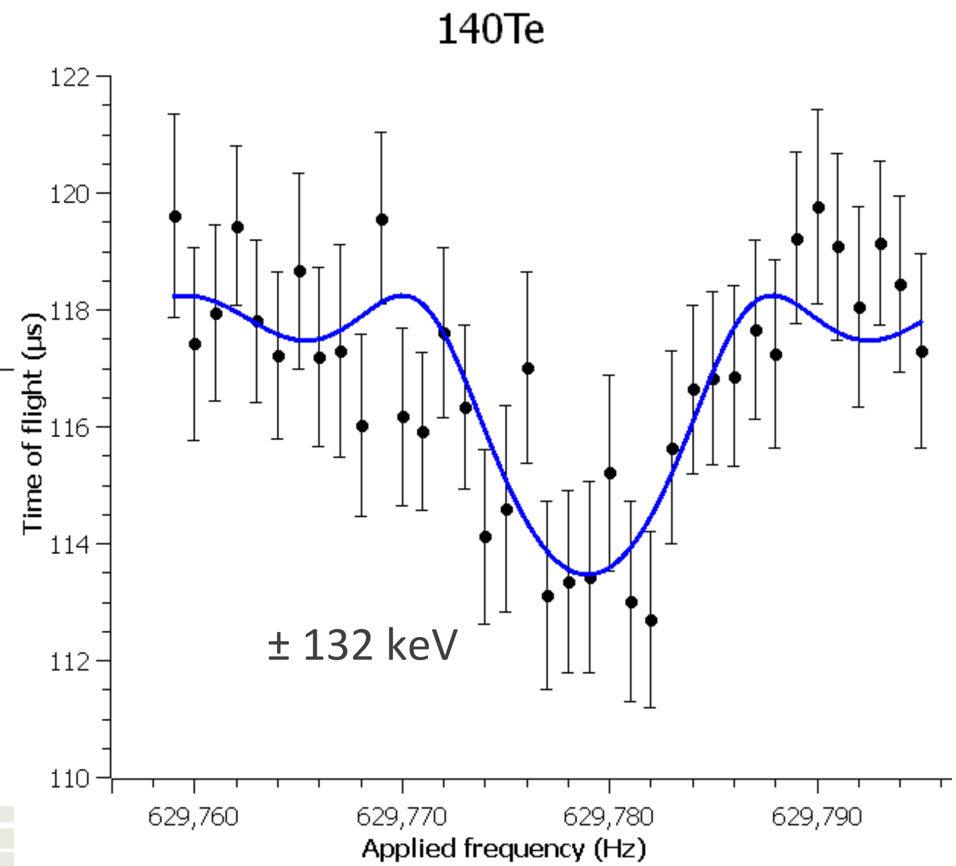
CPT Measurement campaigns



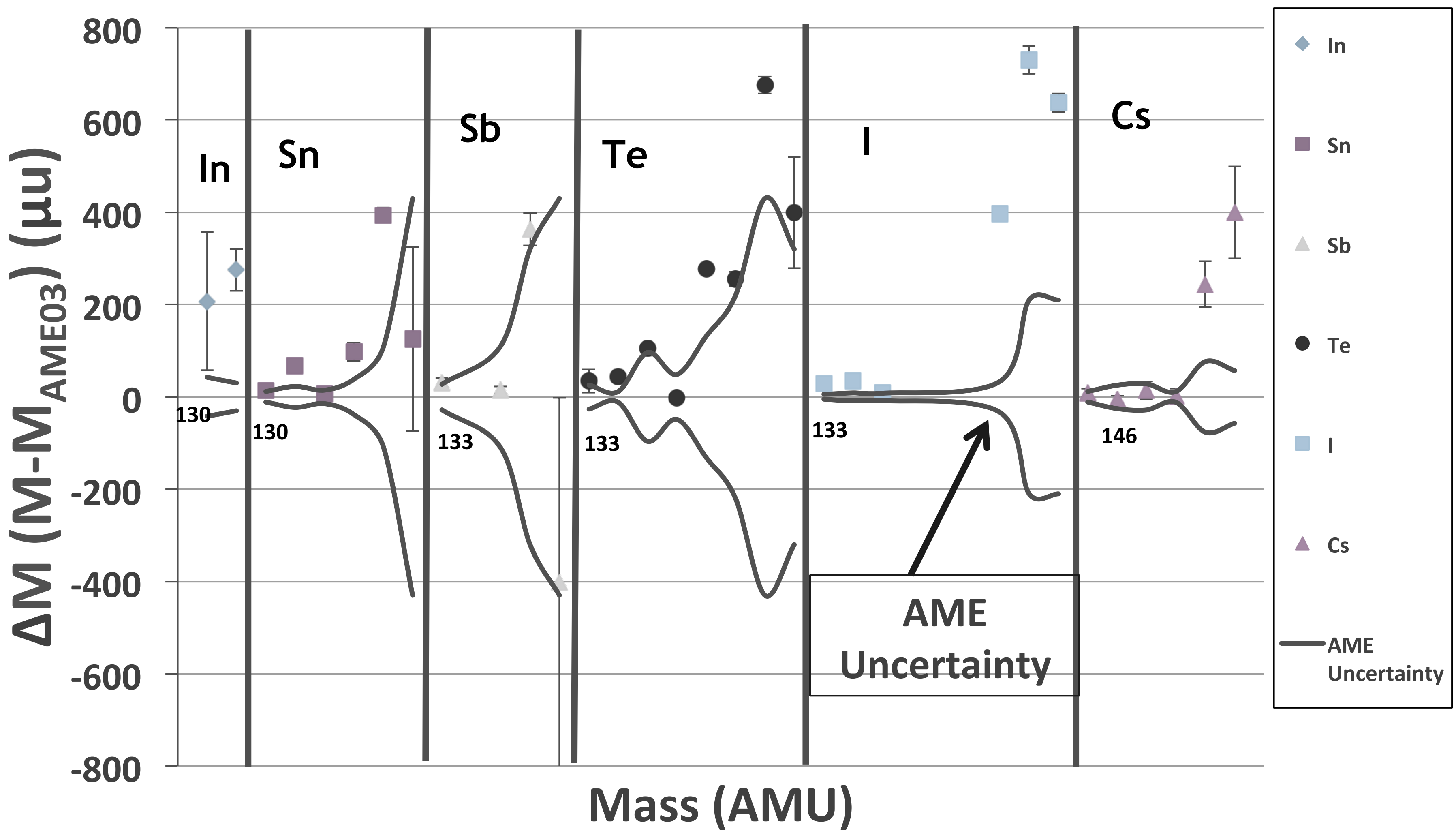
CPT Measurement campaigns




132Sn 1swc
Time of flight (µs)
125
120
115
110
105
100
668,072
668,073
668,074
668,075
Applied frequency
± 3.7 keV

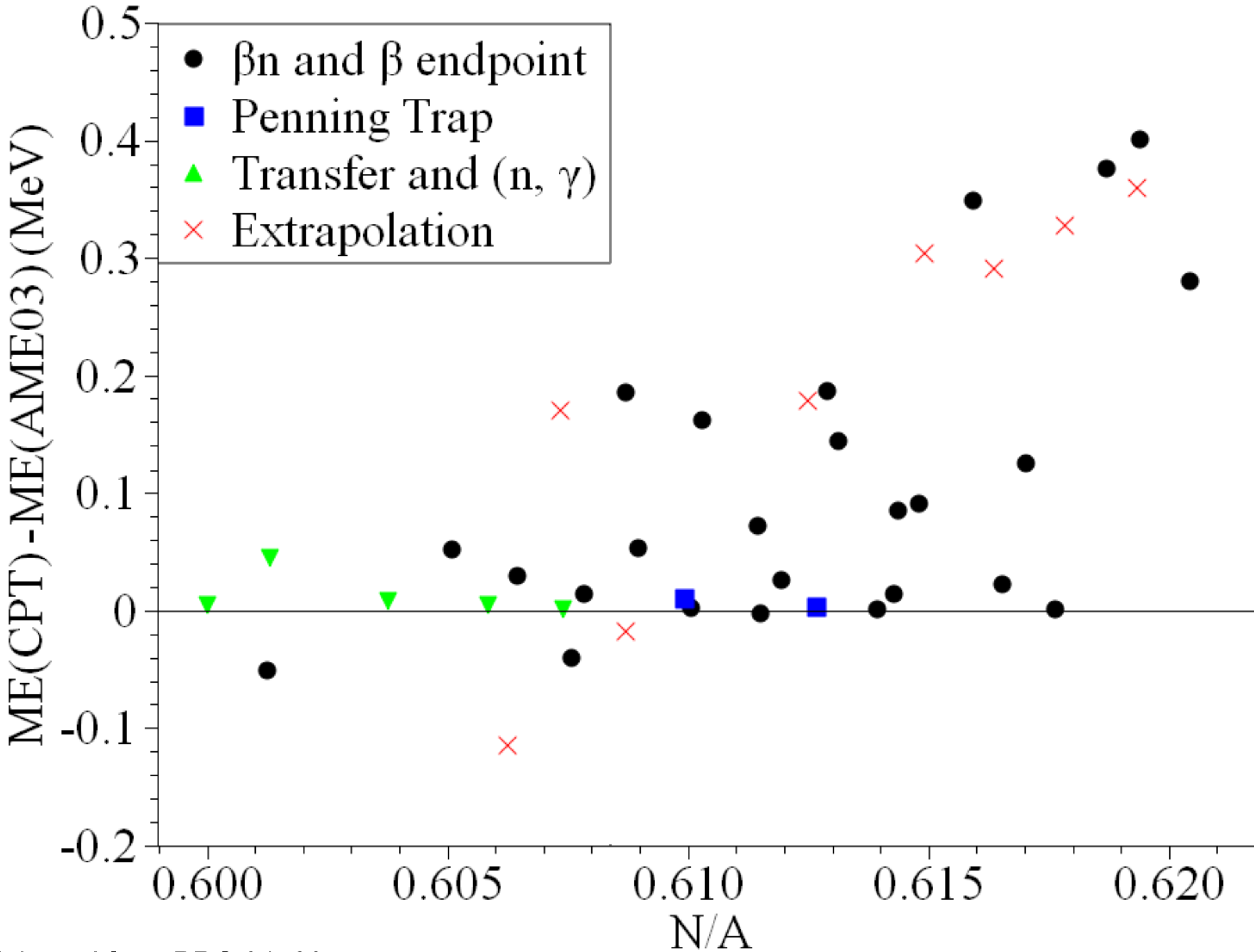

140Te
Time of flight (µs)
122
120
118
116
114
112
110
629,760
629,770
629,780
629,790
Applied frequency (Hz)
± 132 keV

Preliminary Masses Relative to the 2003 AME



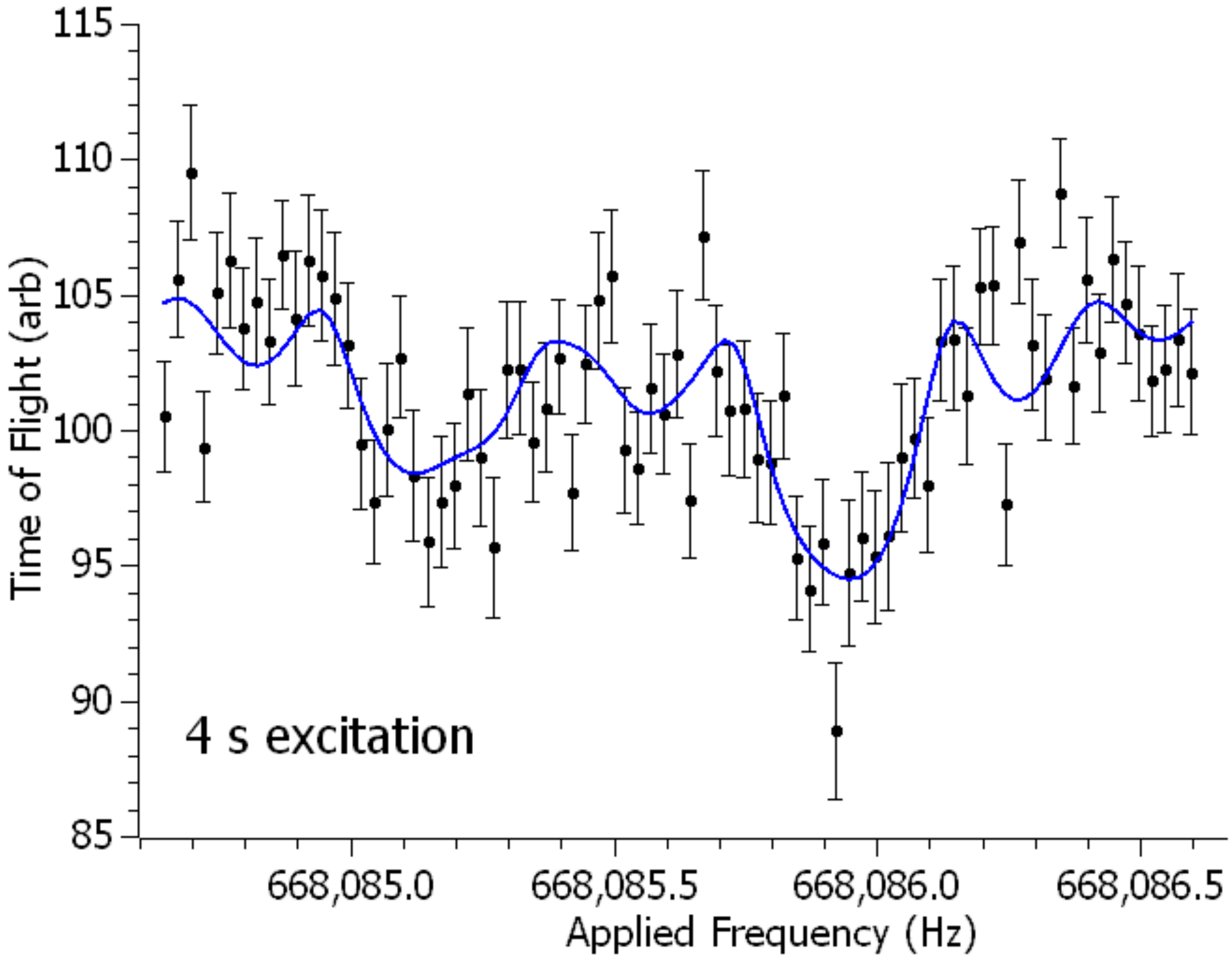
23

Same trend from 2008/9 measurements

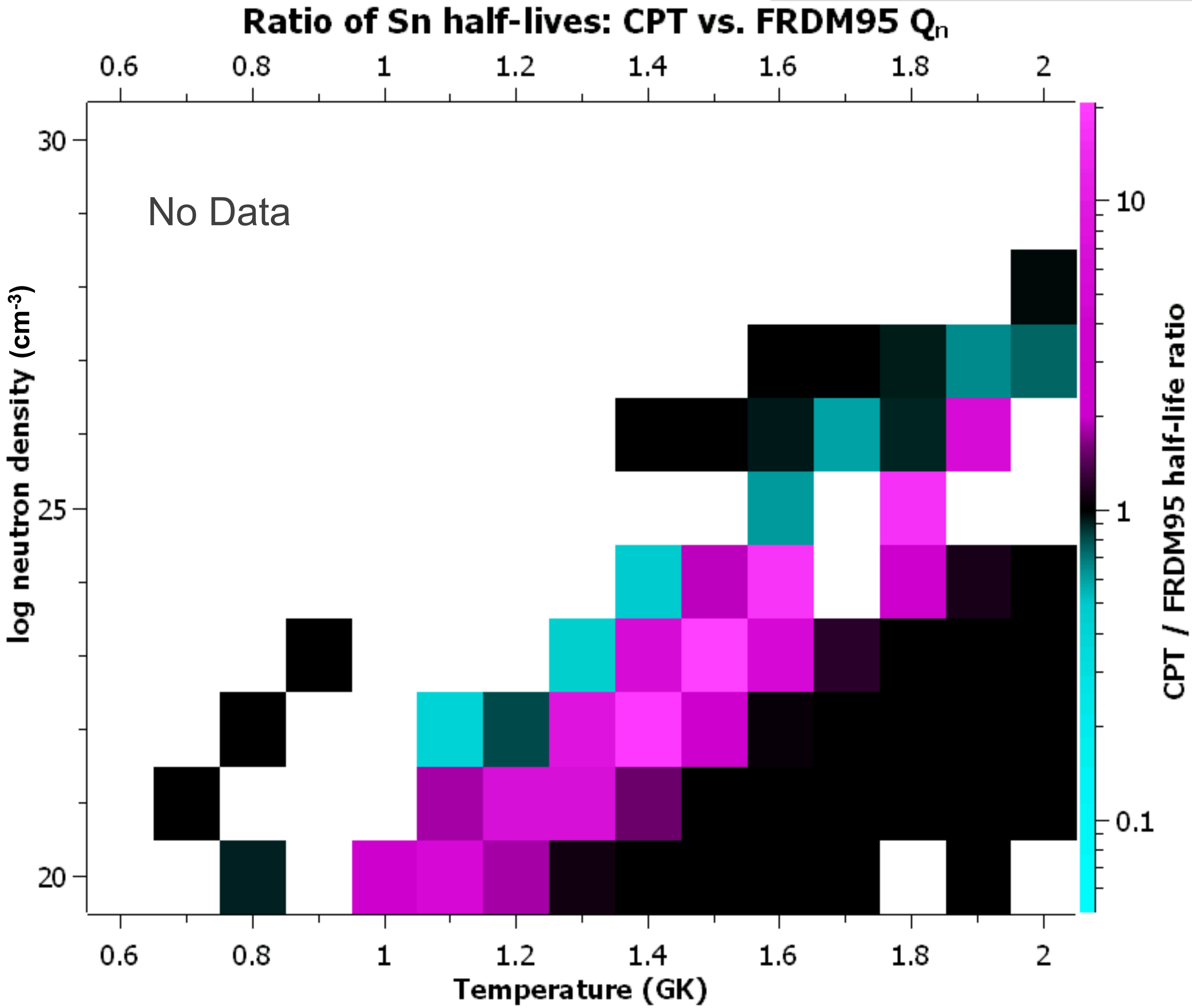


Adapted from PRC 045805

^{132}Sb and $^{132\text{-}m}$Sb



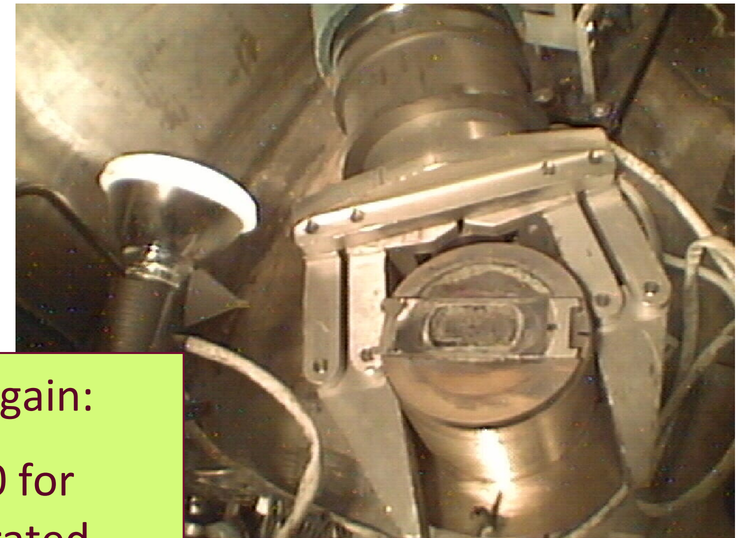
Measurement of isomer excitation energy to 4 keV
No direct measurement, lit: 150-250 keV estimate based on possible level schemes



Ratio of Sn half-lives: CPT vs. FRDM95 Qn
No Data
log neutron density (cm-3)
Temperature (GK)
CPT / FRDM95 half-life ratio
0.6
0.8
1
1.2
1.4
1.6
1.8
2
20
25
30
0.1
1
10

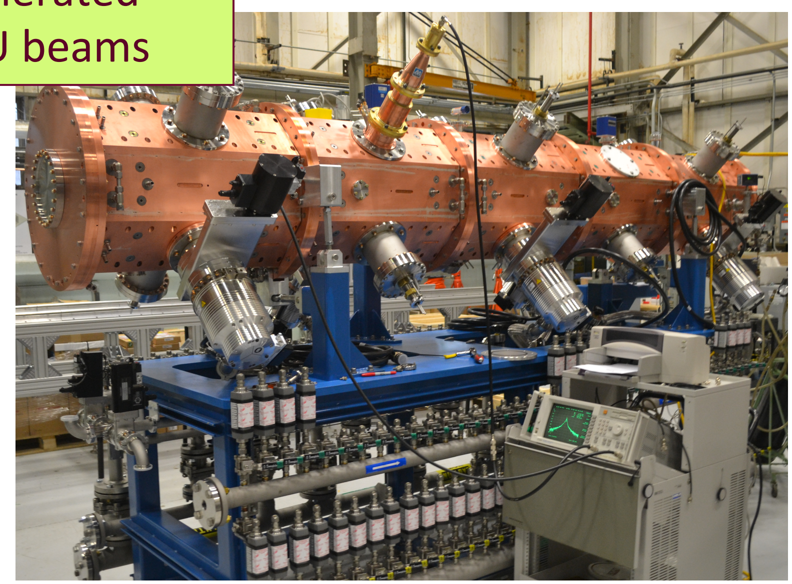
Current efforts (1): Increase intensity of beams

- 1Ci ^{252}Cf source has been fabricated at HIFR reactor in ORNL
  - Actual strength is 500 mCi …. taking it
- Preparing for installation September 4 2012
  - Modifications to shielding and transfer tool
  - Much more paperwork and safety reviews
  - Coordination of transfer HIFR/ANL H
    - Safety envelope of hot cells ready by
    - Remove 50 mCi source August 20
    - Clean up hot cells after transfer follo
    - 500 mCi source installation in cask A
    - Source in cask at CARIBU at end of August
- Ongoing ATLAS upgrade: RFQ installation
  - Main goal
    - Increase max intensity of stable beams
  - Important additional benefit
    - Should remove losses in buncher/PII where most of the ATLAS losses occur
  - Installation Oct. 1 – early Dec.



Intensity gain:

X 10-40 for reaccelerated CARIBU beams

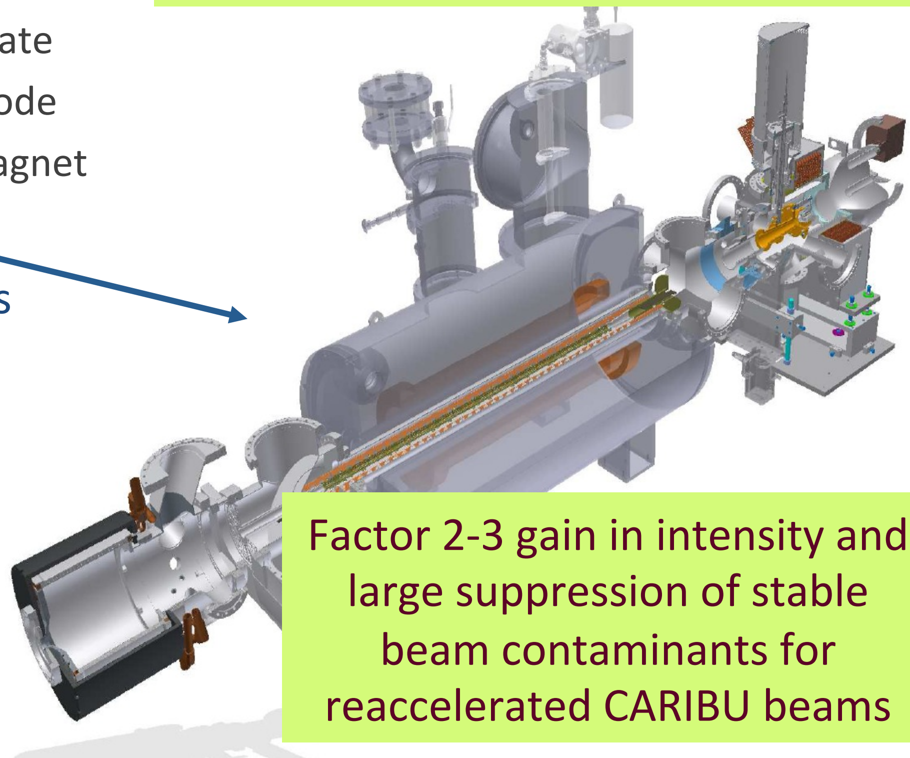


Current efforts (2): Improve beam purity

- Continuous improvements on isobar separator
  - Typical running mass resolution of 10000
- Testing various approaches to reduce beam contamination from ECR charge breeder
  - Liner in ECR source
  - Improved selection in first two bends after ECR
  - Flexibility of choosing cleanest charge state
  - Running part of beamline in gas filled mode
  - Non-equilibrium stripping before last magnet
- Long term solution: EBIS breeder
  - Provides two important gains versus ECR charge breeding at CARIBU
    - Higher charge breeding efficiency demonstrated for pulse injection operation (ANL tests at BNL)
    - Stable beam background suppression

Beam purity:

Good enough for most low-energy experiments and for Coulomb excitation. Should be good enough to start HELIOS CARIBU program in January



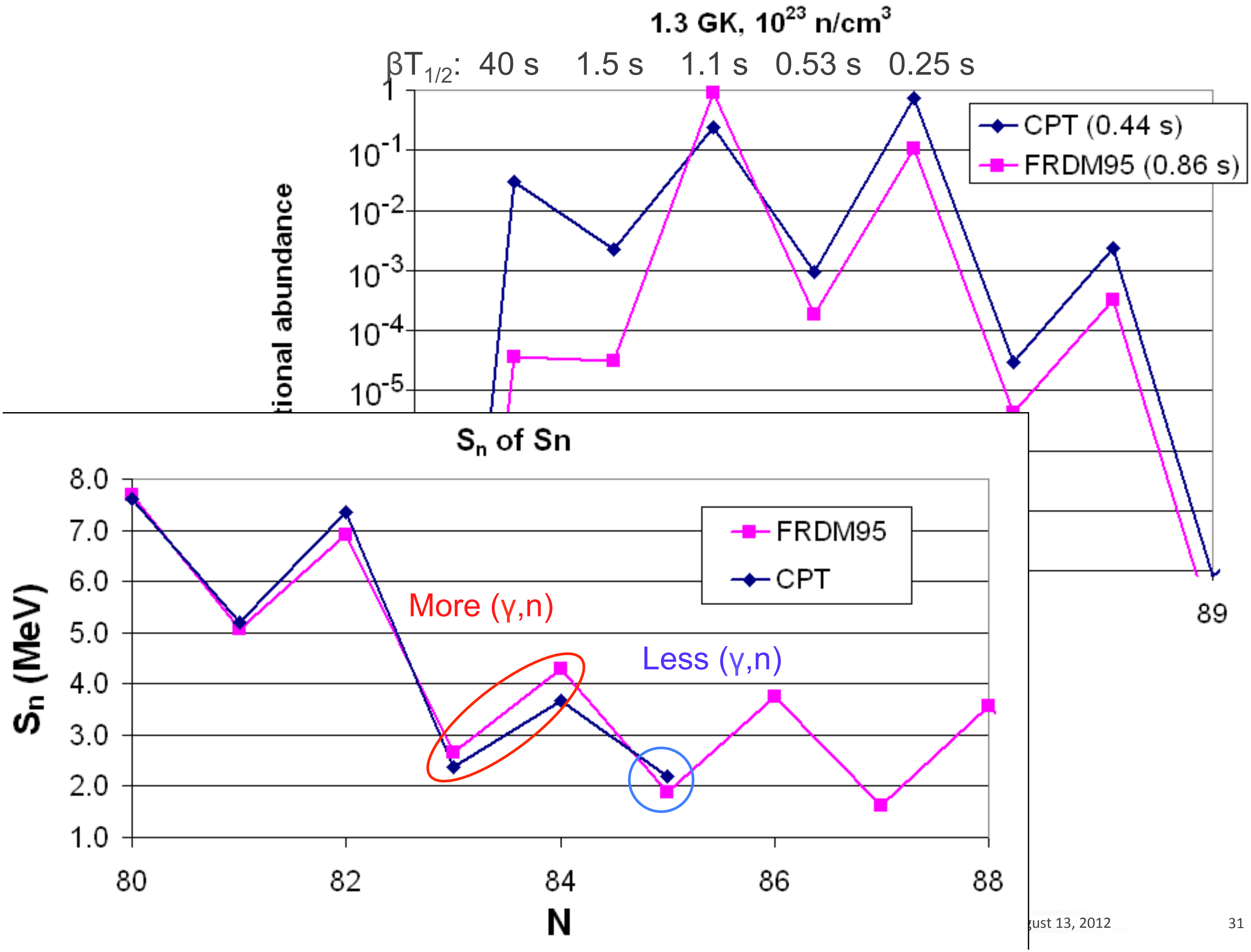
Factor 2-3 gain in intensity and large suppression of stable beam contaminants for reaccelerated CARIBU beams

Status

- CARIBU facility is operational
  - First RIB facility based on a gas catcher … it works
  - Over 70 different neutron-rich radioactive isotope species have been extracted and used for experiments in the last year
  - Low-energy program in full swing with experiments approved by PAC last January taking data
  - Reaccelerated beam program initiated at low intensity

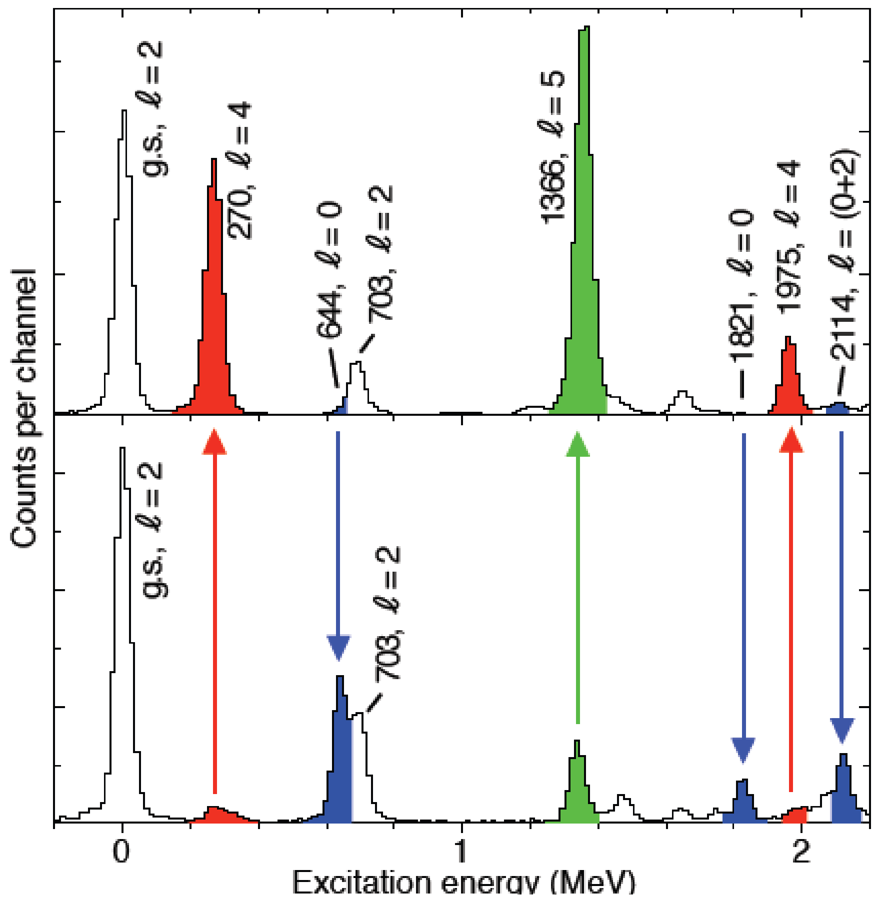
- "1 Ci" source will replace the current 50 mCi source this summer. Combined with RFQ installation this fall, will yield gains of 10 to 40 in intensity for low-energy and reaccelerated beams.

PAC in fall 2012 will accept proposals for reaccelerated neutron-rich beams at energies between 3-15 MeV/u


1.3 GK, 10^23 n/cm^3
βT1/2: 40 s 1.5 s 1.1 s 0.53 s 0.25 s
tional abundance
CPT (0.44 s)
FRDM95 (0.86 s)
89
Sn of Sn
Sn (MeV)
FRDM95
CPT
More (γ,n)
Less (γ,n)
N

Momentum matching

Proton adding – ^{118}Sn(α,t)^{119}Sb versus ^{118}Sn(^{3}He,d)^{119}Sb



Classically, $\underline{\ell} = \underline{r} \times \underline{p}$, so the orbital angular momentum transferred must reflect the linear momentum transfer, at the surface: heavy Q-value dependence.

Good angular momentum matching enhances model (DWBA) validity.